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High Speed Segmental Stator Type 4/3 SRM: Design, Analysis, and Experimental Verification

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Abstract – This paper presents a design of a 2-phase segmental stator type 4/3 switched reluctance motor (SRM) for air-blower application. The air-blower requires only one direction rotation, high rotor speed without torque dead-zone. In order to satisfy the requirements of the load, the rotor of the 4/3 proposed SRM is designed with wider rotor pole arc and non-uniform air-gap is applied on the rotor shape. With a special rotor structure, the motor generates a wider positive torque region and has no torque dead-zone. The stator of the proposed SRM is constructed with two segmental C-cores, and there are no magnetic connections between 2 C-cores. The flux follows in a short closed loop in each C-core and has no reversal flux in the stator. The static and dynamic characteristics of the proposed motor are analyzed by the finite element method (FEA) and Matlab-Simulink, respectively. In order to verify the design, a prototype of the proposed motor has manufactured for laboratory test. The performance of the proposed motor is verified by the simulation and experimental results.

Keywords: Switched Reluctance Motor (SRM), 4/3 SRM, Non-uniform air gap, Short flux path, Segmental stator

1. Introduction

Switched reluctance motor (SRM) has simple structure without permanent magnets (PM), commutator or windings on its rotor. The stator and rotor are laminated by magnetic steel, and the windings are wounded on the stator pole only. The robust structure of the rotor helps SRM can be used for the applications that operated in harsh environments as high temperature and high speed [1-4]. SRM cannot be operated without a power converter, and the number of power switches proportional to the number of phases with the same converter topology. Single- and 2-phase SRM are good candidates for high speed drives because of some advantages such as simplicity of structure, low cost, and low switching frequency. Single- and 2-phase SRM show some disadvantages such as high torque ripple, torque-dead zone, and no self-starting ability. Hybrid structure with PMs, torque dead-zone and self-starting problems of the single-phase SRMs can be solved [5, 6]. The use of PM makes hybrid single-phase SRM less competition compared with other machine as DC motors, and BLDC motors in high speed drive systems. In [2, 4], by modifying the structure and air-gap of the rotor, 2-phase SRMs can be operated at any rotor position without torque dead-zone and reduce the torque ripple. Because the air-gap on the rotor shape is non-uniform, so the motor has asymmetric inductance and torque characteristics with wider positive torque region. These motor type are suitable for unidirectional applications such as air-blowers, compressors, and spindles. Non-uniform air-gap results in low average torque and low efficiency in the 2-phase SRM drives.

This paper presents a design of segmental stator 2-phase 4/3 SRM for air-blower application. In this design, the average torque of the motor is improved and the motor has self-starting ability. The proposed SRM employed four stator poles and three rotor poles. The stator is constructed in two segmental C-cores, and there are no magnetic connection between two C-cores. The flux follows in a short closed loop in each C-core and has no reversal flux in the motor. In order to verify the design, a prototype of the proposed motor has manufactured for laboratory test. The characteristics of the proposed SRM will be compared with the 4/2 SRM in [4]

2. Configuration of the Proposed 4/2 and 4/3 SRM

2.1 Structure of the 4/2 SRM [4]

Fig. 1 shows the structure of the 4/2 SRM has proposed in [4]. In this design, the rotor shape is modified to reduce torque ripple by using combination of finite element method (FEM) and Matlab. The rotor pole optimization algorithm is illustrated in detail in the paper [4]. Single- and two-phase SRM exist the torque dead-zone in the commutation region between phases, and the motor cannot be operated at this region. A simple way to overcome this problem is that design the motor with a wider rotor pole arc, and non-uniform air-gap is applied. The stepper rotor is a

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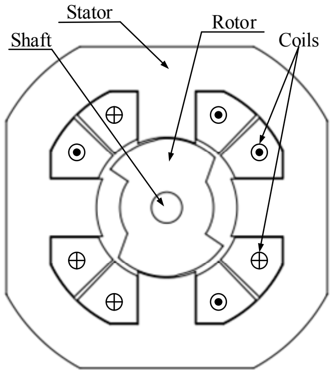
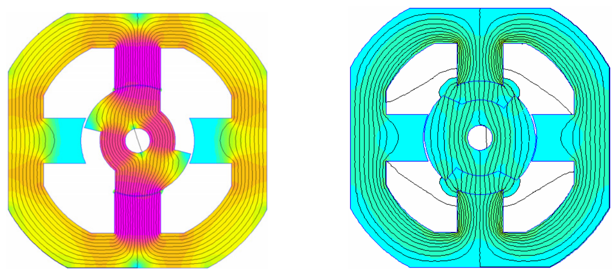


Fig. 1. 4/2 SRM



(a) Full aligned position (b) Flull unaliged position

Fig. 2. Flux distribution in the 4/2 SRM

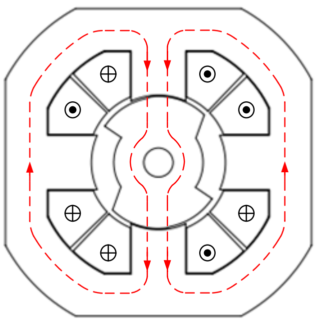


Fig. 3. Flux path in the 4/2 SRM

simple solution in this case, but there is high torque ripple at the stepper position, and an optimization algorithm has proposed in [4] to solve this problem of the stepper rotor type.

Fig. 2 shows the flux distribution in the 4/2 SRM. At aligned position when phase A excited, the rotor is overlapped with the stator of phase B that make sure the motor has overlap torque and self-starting ability. The flux path of the 4/2 SRM is illustrated in Fig. 3. The flux follows in a long closed loop in whole stator.

2.2 Characteristics of the 4/2 SRM

The static characteristics of the 4/2 SRM is analyzed by a 2D FEM software. Fig. 4 shows the torque waveform of the 4/2 SRM at the optimized torque 0.2[Nm]. There is no

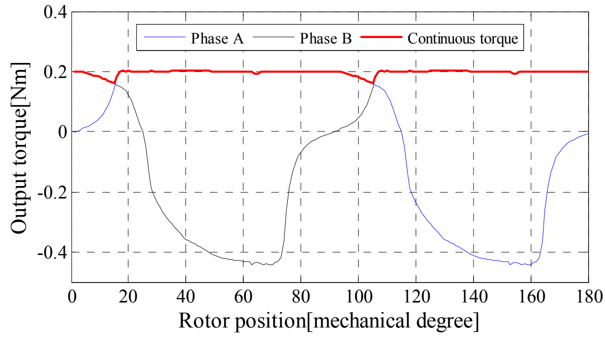


Fig. 4. Torque waveform of the 4/2 SRM

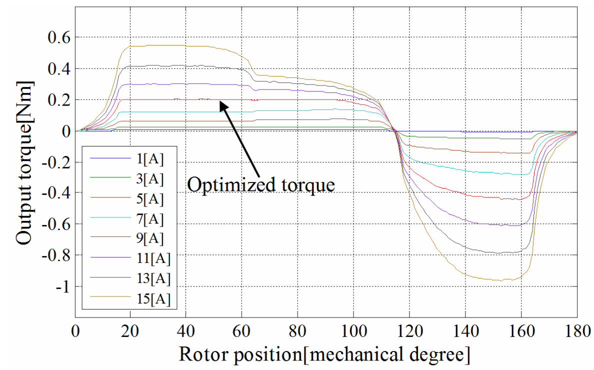


Fig. 5. Torque profiles of the 4/2 SRM

overshoot torque at the flat top and has no torque dead-zone in the commutation region. As shown in Fig. 5, torque ripple increases when load increased. The optimization effects only at the optimized torque, and it is sensitive with the operating conditions and motor structure. Non-uniform air gap makes the motor has low average torque and low efficiency. The average torque can be increased by increase the stator pole arc and reduce the non-uniform air gap region. With a given dimension, when the stator pole arc is increased that results in small winding area, and it not enough space for windings.

2.3 Structure of the proposed SRM

The proposed SRM employed four stator poles and three rotor poles. The stator has a special structure with two segmental C-cores shifted with rotation of 180 degrees. There are no magnetic connection between two C-cores, and has no reversal flux in the motor. In order to increase the winding area, the stator poles is constructed in a special structure as shown in Fig. 6. The windings are wounded on two poles of the C-core in serial connection. The flux path is formed in a short closed loop in C-core when respective phase excited. Short flux path results in lower reluctance and lower core losses compared with long flux path one.

Fig. 7 shows the flux path in the proposed SRM. A motor with the shorter flux path technique has lower reluctance, it means that the MMF required to produce a

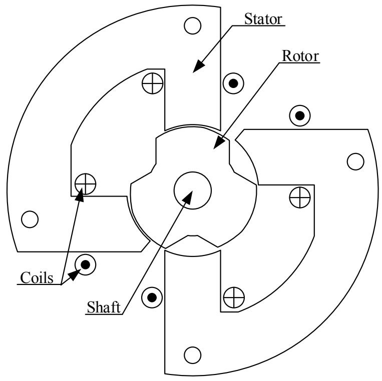


Fig. 6. Configuration of the proposed SRM

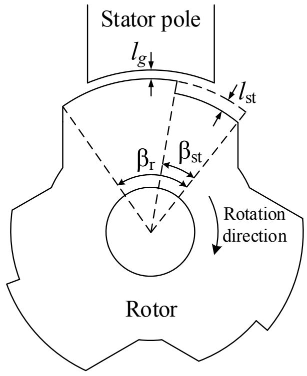
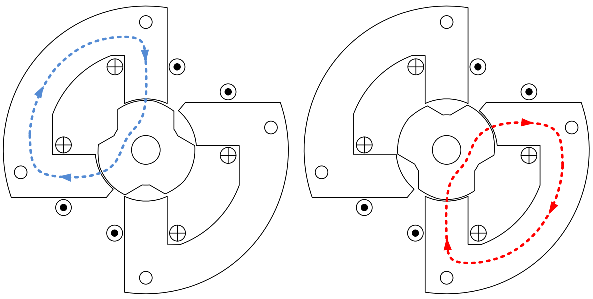


Fig. 8 Stepper rotor



(a) (b)

Fig. 7. Magnetic flux path of the proposed SRM, (a) Phase A; (b) Phase B

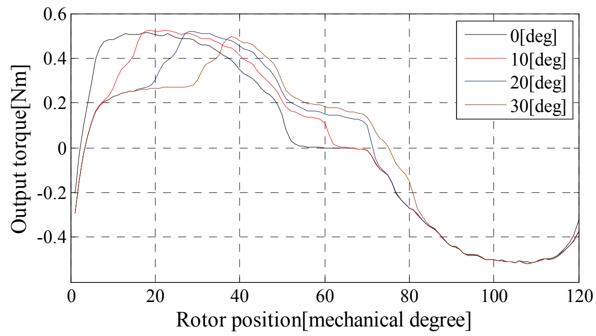


Fig. 9. Torque characteristic of stepper rotor

given flux is smaller than that of long flux path type. The advantage of short flux path is to reduce the core losses and the absorption of MMF in the stator yoke. The proposed SRM has a larger winding area compared with the 4/2 SRM. With the same dimension and limitation of flux density, a higher magnetomotive force (MMF) can be applied for the proposed SRM compared with the 4/2 SRM. Higher MMF is applied that results in higher output torque.

One of disadvantages of the single- and 2-phase motors is torque dead-zone, and the proposed SRM is not an exception. To overcome this problem, a wider rotor pole arc with non-uniform shape was used. Fig. 8 shows the stepper rotor type that will be used in the proposed SRM.

The selection of rotor and stator pole arc follows below rules:

$$\beta_r > \beta_{spr}$$
$$\beta_s \le \beta_{rp} - \beta_r$$
$$\beta_s \ge \beta_{st} \ge \beta_r - \beta_s$$

where β_r, β_s, β_{spr}, β_{rp}, β_{st} is rotor pole arc, stator pole arc, stroke period, rotor pole pitch, and stepper angle, respectively.

The rotor pole arc must be larger than one stroke period to generate the overlap torque in the commutation region. In case of the SRM, the number of electrical strokes of a SRM is a product of number phases n_{ph} and number of rotor poles n_r. The proposed SRM is a 2-phase motor with three rotor poles, so it has six strokes in one rotor rotation, and the stroke period β_{spr} is 60 degrees, it can be calculated by Eq. (1). To satisfy the first rule, a 70 degrees rotor pole arc was selected for the proposed SRM.

$$\beta_{spr} = \frac{360}{n_{ph} \cdot n_r} \tag{1}$$

While the rotor pole is designed larger, the stator pole arc must be smaller or equal to the subtraction of rotor pole pitch and rotor pole arc. The rotor pole pitch of the proposed SRM is 120 degrees and rotor pole arc is 70 degrees, so the stator pole arc must be smaller or equal to 50 degrees. The average torque of a 2-phase SRM is proportional to the ratio of stator pole arc β_s to rotor pole arc β_r. The ideal value of this ratio is equal to 1, but it is impossible in case of 2-phase SRM as well as the proposed SRM. In order to maximize the average torque, a 50 degrees stator pole arc was selected.

Uniform air-gap cannot be used for whole rotor pole of the proposed SRM. If a uniform air-gap is applied on the rotor shape, the motor can generate positive torque in a region of 50 degrees as show in Fig. 9. When the stepper angle β_{st} is equal to zero, it means that the rotor use uniform air-gap. In this case, the output torque is equal to zero when the rotor and stator at full overlap position, and positive torque region only 50 degrees. A stepper is applied

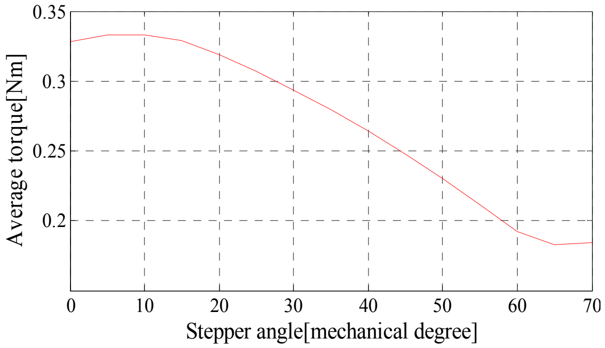


Fig. 10. Average torque vs. stepper angle of the proposed SRM

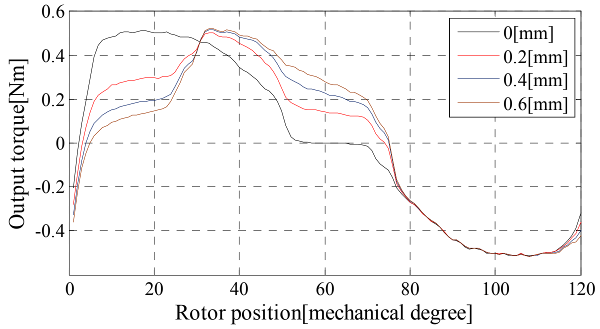


Fig. 11. Output torque vs. stepper air-gap length of the 4/3 SRM

on a part of the rotor pole to extend the positive torque region as shown in Fig. 8. The output torque of the 4/3 SRM with different stepper angle is shown in Fig. 9. In this simulation, the air-gap length l_g is 0.25mm and the stepper air-gap length l_{st} is 0.25mm. The phase winding consist of two coils, each coil has 50 turns, and connected in serial. The phase winding is excited by a DC current 10A. As shown in Fig. 9, when increase the stepper angle, the positive region also increases. But the stepper angle has to satisfy the rule number 3. The stepper angle must be equal or greater than the value of the subtraction of rotor pole arc and stator pole arc, and the maximum value of stepper angle is equal to stator pole arc.

Although increasing of the stepper angle helps the motor generates a wider positive torque region, but it also results in lower average torque. Fig. 10 shows the average torque of the proposed SRM when changing the stepper angle. To maximize the average torque, the stepper angle is selected as small as possible. In case of the proposed SRM, a 22 degrees stepper angle was selected.

Fig. 11 shows the output torque of the proposed SRM when changing the stepper air-gap length l_{st}. When increase the l_{st}, the starting torque is reduced, and the ended torque is increased. High starting torque helps the motor can be started easily, but the ended torque cannot be zero.

Fig. 12 shows the rotor shape of the proposed SRM. The non-uniform air-gap is 22 degrees of the total 70 degrees of the rotor pole. The positive torque is generated during the

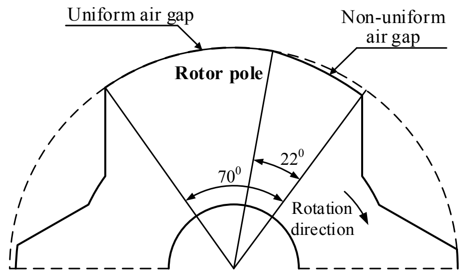


Fig. 12. Rotor shape

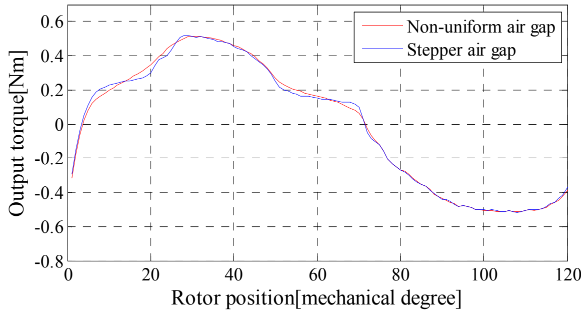


Fig. 13. Comparison torque of non-uniform and stepper air gap type

rising slope of the inductance, it is given in Eq. (2).

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

where T_e is the electromagnetic torque, i is the excited current, and $L(\theta,i)$ is the inductance dependent on the rotor position and phase current.

The inductance in the motor depends on the air-gap length and the overlap area between rotor and stator poles. When the rotor and stator pole are at first overlap region, increasing overlap area results in increasing inductance. Otherwise, when the rotor is at full aligned position, the overlap area is constant, reducing of average air-gap between rotor and stator pole results increasing inductance. So, the motor can produce positive torque during 70 degrees of rotor poles.

Based on the stepper rotor type, the air-gap in the stepper part is modified for torque smoothing. Non-uniform air-gap has no significant effect on average torque. Fig. 13 shows the output torque of the 4/3 SRM with different rotor type.

3. Characteristics of the Proposed SRM

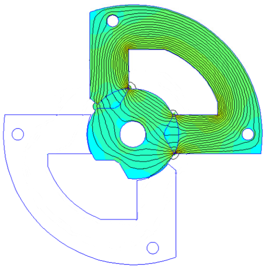
The static characteristics of the proposed motor is analyzed by using a 2D FEA. By using the FEA software, the characteristic of the flux distribution that influences the performance and characteristic of the motor is analyzed. As shown in Fig. 14, the magnetic flux only flows through the respective excited C-core. Actually, small amount of flux flows through the other, but it is not appreciable. Flux density in the motor is kept lower 1.8T.

Torque is one of the important parameters. The designers try to increases the output torque. The higher torque density that means the motor has compact size and low cost. Compared with the others motor which have a uniform rotor shape, the proposed motor has lower torque production. Fig. 10 shows the torque waveform of the proposed SRM at rated current. As shown, the overlap torque is about 10 degrees. This overlap torque make sure the motor can be operated at any rotor position without the torque dead-zone and has self-starting ability.

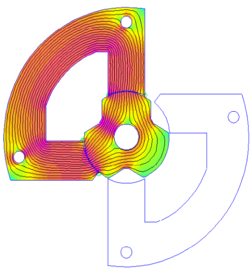
Fig. 16 and 17 show the torque and inductance profiles of the proposed SRM, respectively. The 4/2 and proposed SRM have asymmetric inductance and torque characteristics with wider positive region. Because of these characteristics, the 4/2 and proposed SRM are suitable for unidirectional rotation application.

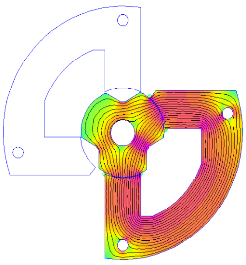
Fig. 18 shows the comparison average torque of the 4/2 SRM and the proposed SRM. With the same MMF, the proposed SRM generates higher average torque compared with the 4/2 SRM. When a MMF 450[AT]/pole is applied for both motors, the average torque of the 4/2 SRM is 0.198[Nm] while that of the proposed SRM is 0.279 (40% higher). Higher output torque makes a motor has a compact size and low cost.

Fig. 19 shows the performance comparison of the proposed and 4/2 SRM. Two motors are designed with the same dimensions, and the specifications of the 4/2



(a) Unaligned position





(b) Phase A excited (c) Phase B excited

Fig. 14. Flux distribution in the proposed SRM

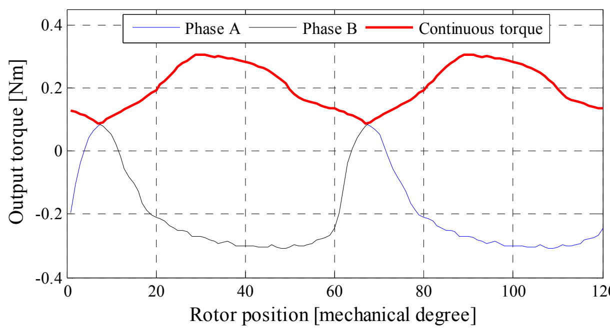


Fig. 15. Torque profiles

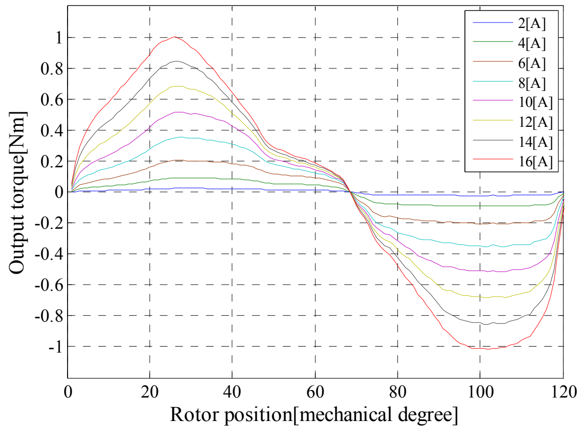


Fig. 16. Torque profiles

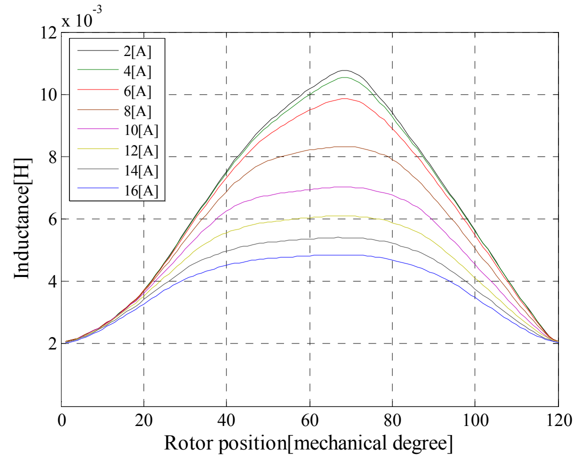


Fig. 17. Inductance profiles

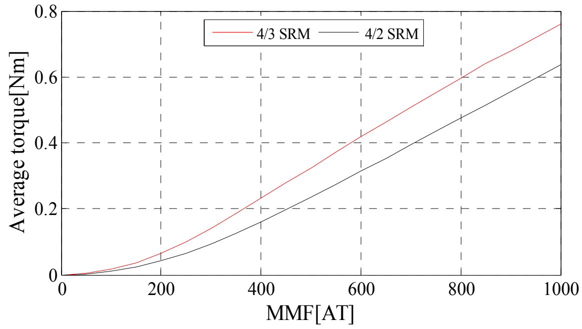


Fig. 18. Comparison torque of the 4/2 SRM and the proposed 4/3 SRM

and proposed 4/3 SRM are given in Table 1. There are 8 parameters selected for performance comparing. Because of the special structure, the proposed SRM has larger space for winding, and it can generate higher torque as well as output power compared with the 4/2 SRM. The proposed SRM is better in average torque, peak torque, max power, power-to-weight ratio, and efficiency compared with the 4/2 SRM. While the 4/2 SRM is better in max speed and lower torque ripple compared with the proposed SRM. The proposed SRM is characterized by high torque and efficiency. It is suitable for the applications that require high torque density like rotary hammer, hitter while the torque ripple is not a serious problem. The 4/2 SRM is good for very high speed application like air-blower, compressor.

Fig. 20 shows the prototype of the proposed SRM. The dimensions of the prototypes are given in Table 1. The manufacturing of the proposed SRM is more difficult compared with the 4/2 SRM. Because the stator is separated into two cores without the steel connection. The stator cores are fixed in the cover by four screws. There are some mechanical errors that make the air-gap not the same at any positions around the rotor. So the assembling of the motor has to be done carefully and exactly.

Fig. 21 and 22 show the measured and FEM analysis inductance and torque vs. rotor position of the proposed SRM, respectively. As shown in this figure, the measured

Table 1. Specifications of the 4/2 and proposed 4/3 SRM

Parameters	4/2 SRM	4/3 SRM	Unit
Outer diameter	90	90	mm
Bore diameter	32	32	mm
Stack length	33	33	mm
Rotor pole arc	70	102	degree
Stator pole arc	45-50	48	degree
Air gap	0.25-0.6	0.25-0.65	mm
Rated torque	0.2	0.2	Nm
Operating speed	10,000	10,000	rpm
Operating power	210	210	W

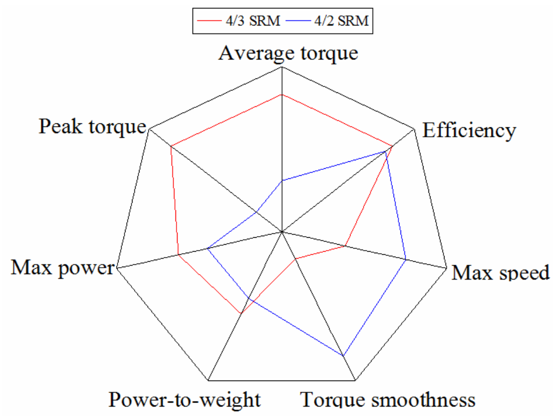


Fig. 19. Performance comparison of the proposed and 4/2 SRM

Fig. 20. Prototype of the proposed SRM: (a) Rotor; (b) Stator; (c) Full assembly of the proposed SRM

Table 2. Performance comparison of the 4/2 and proposed SRM

Parameters	4/2 SRM		4/3 SRM	
	Simulation	Measurement	Simulation	Measurement
Speed[rpm]	10,000	10,000	10,000	10,000
Torque[Nm]	0.2	0.2	0.2	0.2
Input power [W]	265.3	302.9	258.8	274.5
Output power[W]	209.6	209.6	209.6	209.6
Efficiency	79	69.2	81	76.4

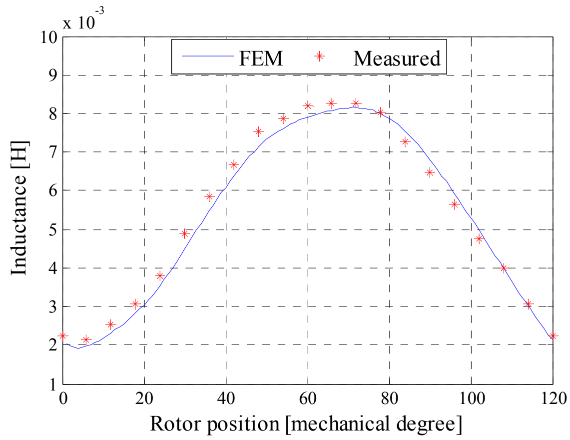


Fig. 21. Measured and FEM analysis inductance vs. rotor position of the proposed SRM

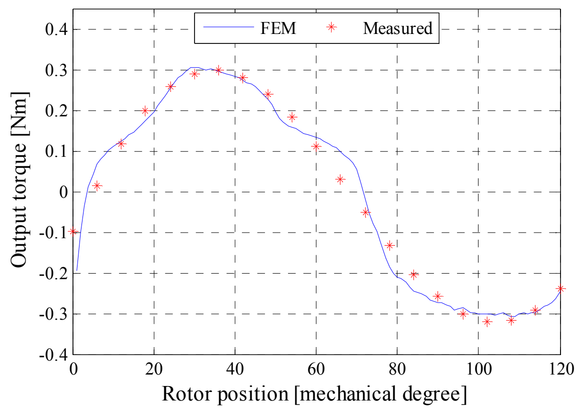


Fig. 22. Measured and FEM analysis torque vs. rotor position of the proposed SRM

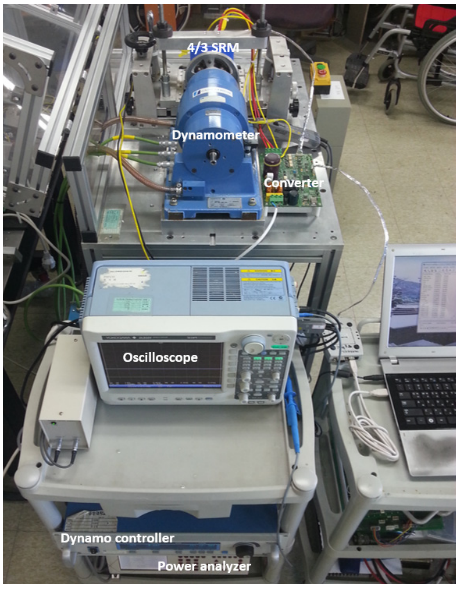


Fig. 23. Experimental setup

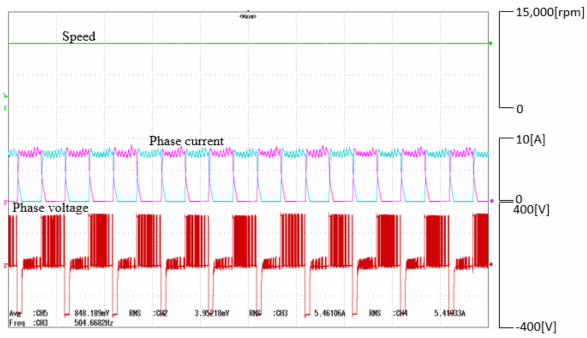


Fig. 24. Experimental result of the proposed SRM with load torque 0.2[Nm] at 10,000[rpm]

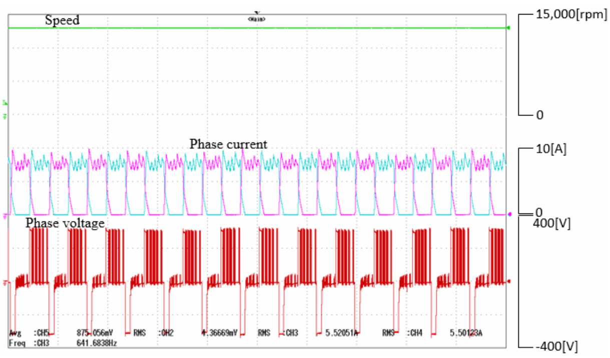


Fig. 25. Experimental result of the proposed SRM with load torque 0.2[Nm] at 13,000[rpm]

flux linkage well match to that of predicted by FEM. The error for unaligned and aligned position is less than 8%.

Fig. 23 shows the experimental setup of the proposed SRM drive system. The load is supplied by the adjustable dynamometer. The output power is measured by high-speed dynamometer 2WB43, and the input power is

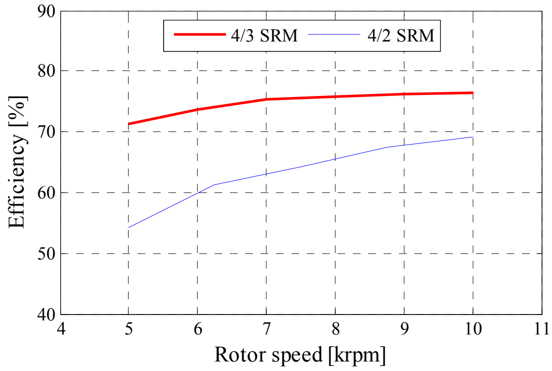


Fig. 26. Performance vs. rotor speed of the 4/2 SRM and the proposed SRM

measured by the power analyzer PPA2530.

The prototyped is tested with dynamometer, the experimental results at 10,000rpm and 13,000rpm are shown in Fig. 24 and 25, respectively. Table 2 shows the performance comparison of the 4/2 and the proposed SRM. The measured efficiency of the proposed SRM is 10.4[%] higher than that of the 4/2 SRM. The differences between simulation and measurement are from mechanical losses and windage losses that were not considered in the simulation model. Fig. 26 shows the performance vs. rotor speed of the 4/2 SRM and the proposed SRM.

5. Conclusions

This paper presents design and analysis of a high-speed segmental stator type 4/3 SRM. In order to produce a continuous output torque, the positive torque region is extended with an asymmetric inductance characteristic. The proposed SRM has extended positive torque region and the air gap is non-uniform with a torque over-lap region between phases. The proposed motor is suitable for unidirectional rotation application. A prototype of the proposed motor has manufactured and tested to verify the design. The proposed SRM has shown a better performance compared with the 4/2 SRM in [4].

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