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Design and Operation Characteristics of Novel 2-Phase 6/5 Switched Reluctance Motor

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Abstract – This paper presents a design of novel 2-phase 6/5 switched reluctance motor (SRM) for an air-blower application. This type of motor is suitable for the applications that require high speed and only one directional rotation as air-blower. The desired air-blower is unidirectional application, and requires a wide positive torque region without torque dead-zone. In order to get a wide positive torque region without torque dead-zone during phase commutation, asymmetric inductance characteristic with non-uniform air-gap is considered. The proposed motor can be operated at any rotor position. The proposed 6/5 SRM uses short flux path technique that achieved by means of winding configuration and lamination geometry. The purpose of short flux path is to reduce the core loss and the absorption MMF in the stator. The proposed 2-phase 6/5 SRM is verified by finite element method (FEM) analysis and Matlab-Simulink. In order to verify the design, a prototype of the proposed motor was manufactured for practical system.

Keywords: Switched reluctance motor (SRM), 2-phase 6/5 SRM, Short flux path, Non-uniform air-gap

1. Introduction

In recent, high speed motor drives are much interested in the practical applications to reduce the system size with an increased efficiency. Especially, blowers, compressors, pump and spindle drives are suitable for the high speed motor drives. The demand for the high speed motor system is much increased according to the industrial market. For a practical system, various electric machines are researched to apply for the high speed application such as DC motors, permanent magnet machines and SRMs.

SRM has simple structure and inherent mechanical strength without rotor winding or permanent magnet. These mechanical structures are suitable for harsh environments and high temperature and high speed applications [1-4].

This paper presents of a 2-phase 6/5 SRM for an air-blower. In this application, the impeller rotates only one direction, and it requires a wide positive torque without torque dead-zone.

The proposed 6/5 SRM has self-starting ability without torque dead-zone. The 6/5 SRM is designed with 6 stator poles and 5 rotor poles. In order to get a wide positive torque region without torque dead-zone during phase commutation, asymmetric inductance characteristic with non-uniform air-gap is considered.

The desired motor is employed short flux path [5-7]. This is an advantage of 6/5 SRM. The advantages of short flux path are to increase the efficiency and torque production while decrease the core loses.

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2. Design of the 2-Phase 6/5 SRM

The dimensions of the 6/5 SRM were calculated according to the given output power, rated torque, rated speed and considerations of the dimension limited conditions. The calculations based on the relationship between mechanical energy and electrical energy explained by electromechanical energy conversion principle. In addition, the flux density, the magnetic saturation and the coil fill factor are also considered. The geometry structure and magnetic circuit will be verified by FEM software and Matlab-Simulink. To satisfy the requirements of air blower application, the 6/5 SRM was designed with dimensions as provided in Table 1.

2.1 Configurations of 6/5 SRM

Fig. 1 shows the 2-phase 6/5 SRM structure. The proposed motor has 6 stator poles and 5 rotor poles. The stator is separated into two cores with three poles each, and

Table 1. The specifications of the proposed 6/5 SRM

Parameters	Value	Unit
Output power	314	W
Stator poles	6	
Bore diameter	34.6	mm
Stack length	30	mm
Stator pole arc	22-32	Deg
Average torque	0.2	Nm
Rotor poles	5	
Stator outer dia.	84	mm
Air-gap	0.3-0.6	mm
Rotor pole arc	44	Deg

between these cores have no steel lamination. To keep the rotor poles do not touch into the stator poles, the stator core is fixed by an aluminum plate. The plate has no influences on flux distribution of the proposed motor. Each phase consists of windings on three poles of the E-core, and these windings are connected in serial. With this structure, the magnetic flux flows through the stator core are to be shortest.

The stator is divided into two E-cores with three stator poles for each, in which the middle stator pole arc is greater than other ones. Two smaller stator poles are designed with a half of rotor pole arc. The angle between two stator poles adjacent in E-core is 72° that equal to one rotor pole pitch. The stator coil is wrapped round each stator pole with direction as shown in Fig. 1, and these coils are connected each other in serial. Two E-cores are shifted an angle 180°, and each E-core is one phase.

A disadvantage of the one-phase and 2-phase motor is self-starting ability, and the 6/5 SRM is not an exception. To overcome the torque dead-zone problem, the 6/5 SRM uses a uniform rotor shape and an asymmetric inductance profile.

Fig. 2 shows the rotor shape of the 6/5 SRM. The main purpose of this rotor type is to expand the positive torque by means increase the positive inductance variation. The rotor shape is divided into two regions, and the rotor radius of the first region is smaller than the second one. The

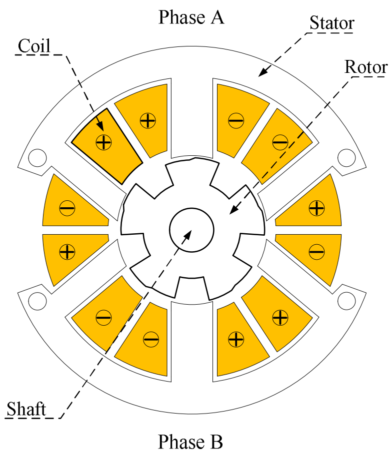


Fig. 1. 2-phase 6/5 SRM structure

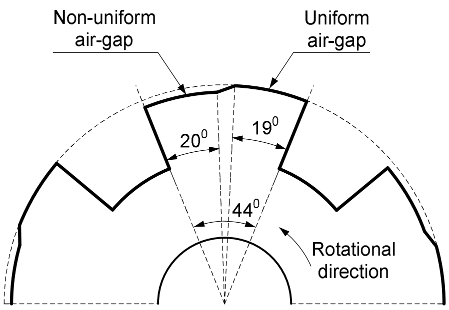


Fig. 2. Rotor shape

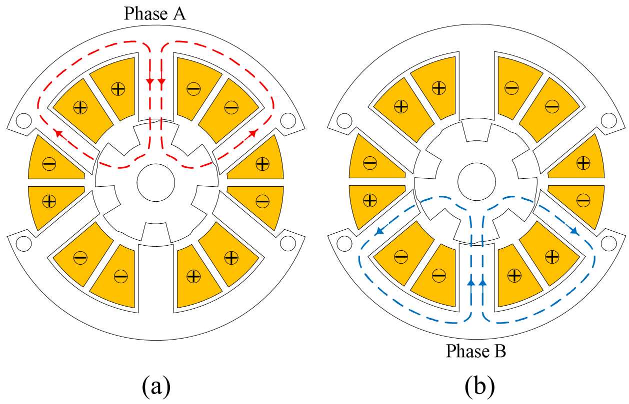


Fig. 3. Magnetic flux path (a) Phase A; (b) Phase B

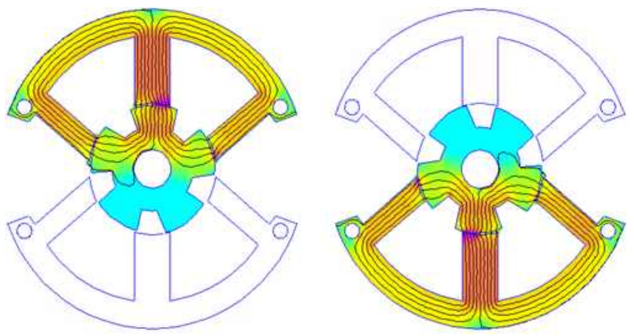
effects of this rotor shape like as the stepper rotor shape. With geometric structure, the inductance in the motor depends on the air-gap length and overlap area between rotor and stator poles.

In the first region, the increase of inductance is the result of the increase of overlap area between rotor and stator. The rotor radius is kept constant in this region. And when rotor rotated by 22°, which equal to stator pole arc, the rotor and stator are full overlap, and the overlap area is constant. In the second region, the increase of inductance is due to the reduction of average air-gap length. The overlap area consists of two areas that are the areas with smaller and lager air gap. The inductance is increased by increasing the smaller air-gap area until the first region is out of overlap region. So the inductance is increased during rotor rotation, 44°.

Fig. 3 shows the magnetic flux path in the proposed 6/5 SRM at the aligned position. The magnetic flux path is divided into two closed loops, in which middle stator pole is shared. Because the E-cores were separated, so magnetic flux in the E-core cannot flow through each other. The flux path in the 6/5 SRM is shorter than conventional ones. A shorter flux path results a lower reluctance in stator core that means it needs lower MMF to produce the same torque. So, a motor with short flux path can reduce current amount or winding-turns with the same output torque.

2.2 FEM analysis

The SRM has nonlinear characteristic, the torque production depends on both current and rotor position. An FEA is needed to verify the design as well as for simulation of the proposed motor. In this paper, the FEMM software is used, it is free software. The FEMM is used in combination with Matlab to analyze the motor characteristic. The motor characteristics such as torque production, flux-linkage, and inductance are calculated by using FEEM. The data obtained from FEM analysis will be used for simulation of the 6/5 SRM drive system. Fig. 4 shows the flux distribution in the 6/5 SRM. To get a high torque density, the 6/5 SRM is analyzed at saturation state of magnetic



(a) (b)

Fig. 4. Flux distribution (a) Phase A; (b) Phase B

material. Because the stator of the 6/5 SRM with two E-cores are separated, so the magnetic flux flows through only in E-core with respective phase excitation. There is no fringing or mutual flux linkage between two phases. The 6/5 SRM also has no revert magnetic flux, for this reason, the core losses is reduced.

Torque is one of most important parameters. The designers try to increases torque with efficiency. The higher torque density that means the motor size and the cost can be reduced. In this paper, the desired air-blower requires a wide positive torque without torque dead-zone. When calculated the dimension of the motor, only average torque was considered. But torque is a function of both rotor position and phase current, and it varies vs. rotor position with a given current. Torque is analyzed with phase current from 0 to a current amount where the motor achieved saturation state as shown in Fig. 5, in which the torque characteristic at rated value is most important. Compared with the others motor which have a uniform rotor shape, the proposed motor has lower torque production.

Torque characteristics depend on the relationship between flux linkages and rotor position as a function of phase current. Torque varies with rotor position and phase current. The torque production can be estimated by (1).

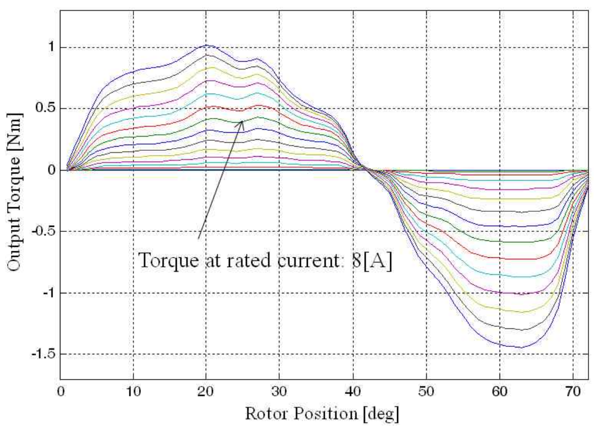


Fig. 5. Torque profile

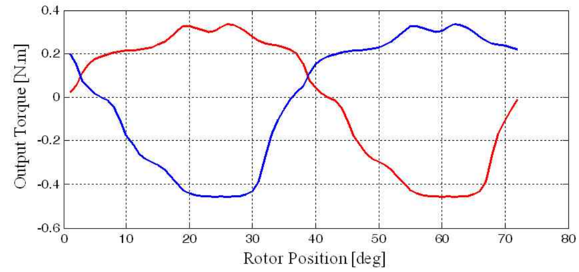


Fig. 6. Output torque of 2 phases

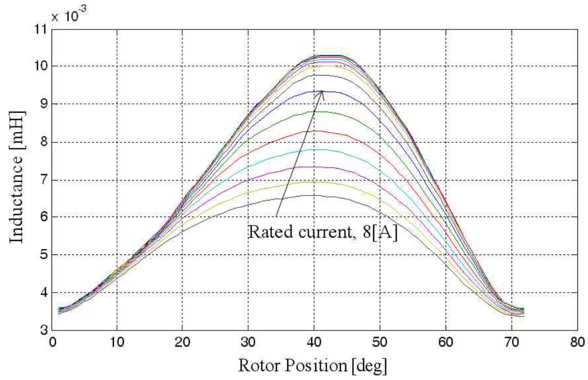


Fig. 7. Inductance profile

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

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.

By using the 2D FEA, the inductance and torque characteristics are analyzed. Fig. 5 shows the torque profile of the proposed motor. Fig. 6 shows that the overlap torque is about 10 degree. This overlap torque ensures that the motor can be operated without the torque dead-zone and has self-starting ability.

Fig. 7 shows the inductance profile of the proposed motor. Because of uniform rotor shape, the 6/5 SRM has asymmetric inductance and torque profile with a wider positive region. This characteristic of inductance makes 6/5 SRM is suitable for unidirectional rotation devices as air blower in this study.

Similar as torque, the inductance is also analyzed with various given current until reach the saturation state. The unaligned inductance is about 3.5 [mH] while the aligned inductance is about 9.3 [mH]. The unaligned inductance effects on the rising time of current that is the time from 0 [A] to desired current, it is important in high speed SRM. If the unaligned inductance is high, a high voltage to build up the current to desired value is needed.

3. Experimental Results

In order to verify the proposed design, a prototype was

(a) Rotor

(b) Stator

(c) Assembled 6/5 SRM

Fig. 8. Prototype 6/5 SRM

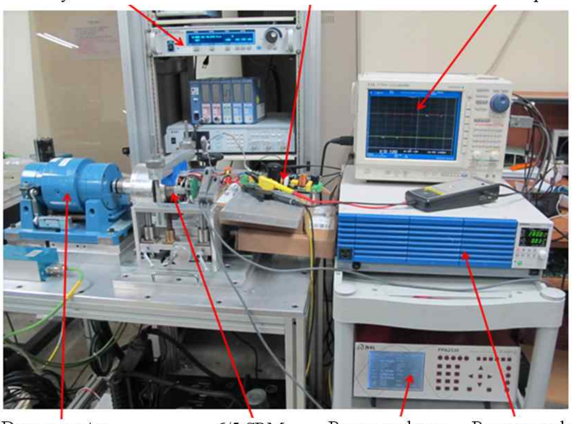


Fig. 9. Experimental setup

manufactured for practical system. Fig. 8 shows the prototype of the proposed 6/5 SRM. The prototype was manufactured with specifications as shown in Table 1.

Fig. 9 shows the experimental setup of the 6/5 SRM drive system. The load is supplied by the dynamometer and the output power is measured by high-speed dynamometer 2WB43. The input power is measured by the power analyzer PPA2530. Fig.10 shows the 2-phase asymmetric converter of the motor control system. Current of the motor is measured by a current sensor (ACS712) and embedded 12-bit ADC of DSP (TMS320F2811). The DC link voltage is measured by a voltage sensor (A-788J) and embedded ADC.

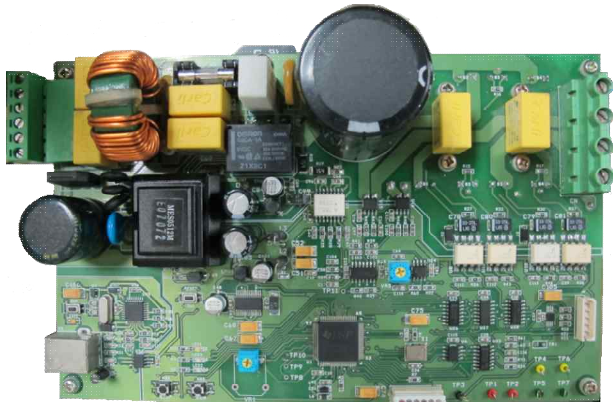


Fig. 10. High speed 2-phase converter

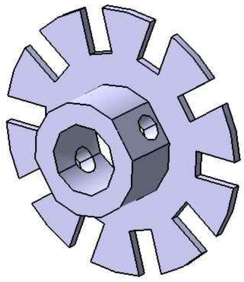


Fig. 11. Rotor position sensor

Fig. 12. Universal motor

The rated speed of the 6/5 SRM is 15,000 [rpm], normal optical encoders cannot work because of mechanical problem. A low resolution rotor position sensor was used to detect the rotor position and determine the rotor speed as shown in Fig. 11. The rotor position sensor has 10 pulses per revolution with the ultra fast opto-coupler. The signal from position sensor is connected to the QEP module of DSP to determine the turn-on, turn-off angle and the rotor speed.

The proposed motor was designed to replace the universal motor that used in the hand-dryer machine. The universal motor is shown in Fig. 12. The proposed motor dimension is the same with that of the universal motor. Fig. 13 shows the proposed motor with an air blower.

Fig. 14 shows the control scheme for the 6/5 SRM. There are two controllers: current and speed controller. Output of speed controller is command current for current

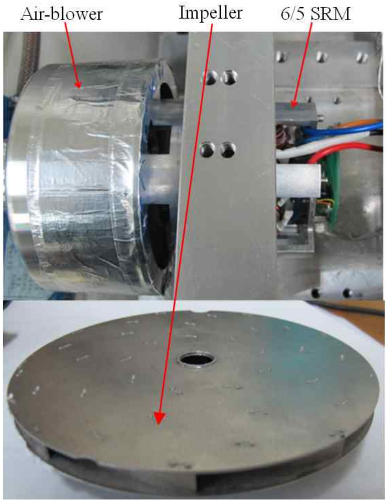


Fig. 13. Proposed motor with air blower

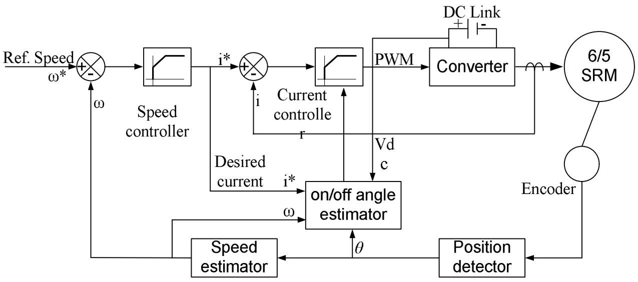
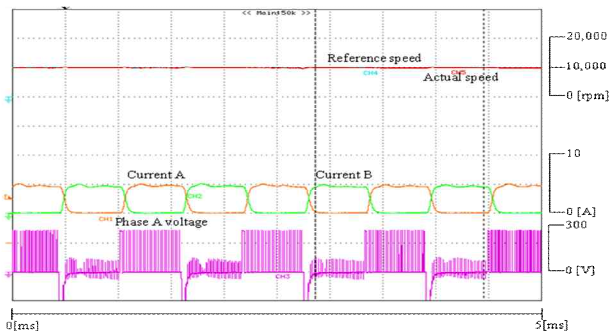
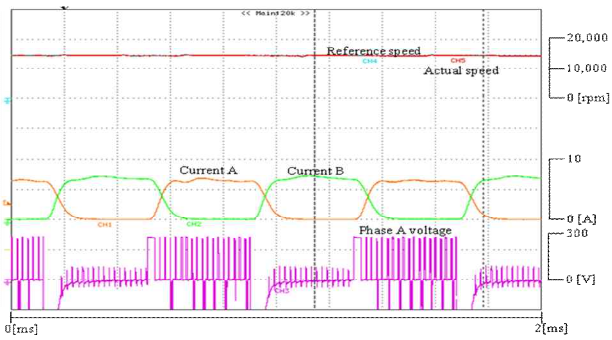


Fig. 14. Control scheme for proposed 6/5 SRM



(a) At 10,000[rpm]



(b) At 15,000[rpm]

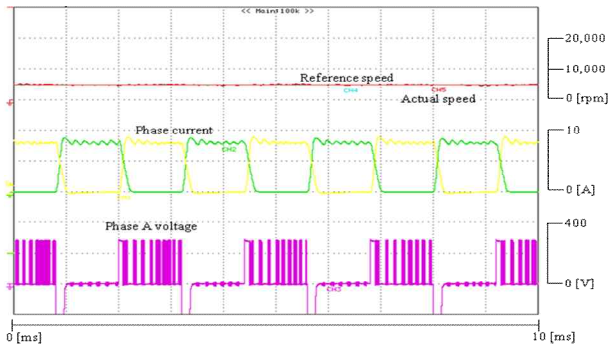
Fig. 15. Experimental results of proposed motor with air-blower

controller. Current limiter block is to limit command current below allowable current value. Output of current controller is command voltage for PWM generator.

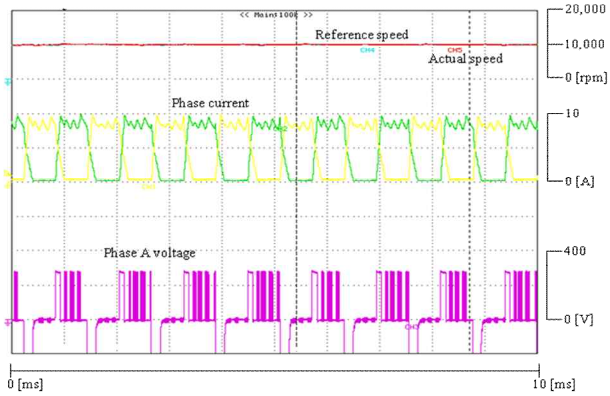
Fig. 15 shows the experimental results of the proposed motor with air-blower at 10,000[rpm] and 15,000[rpm], respectively. Current controller was applied for proposed motor scheme. As shown in Fig. 15, there is no over-shoot on phase currents.

The output and input power are mesured by high speed dynamometer 2WB43 and power analyzer PPA2530, respectively. Fig. 16 shows the experimental results of the proposed 6/5 SRM with dynamometer.

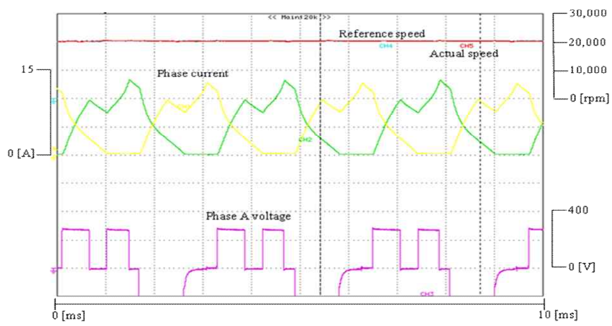
The total efficiency of the motor driver system at rated value, including the power converter and motor is 75.3% as



(a) At 5,000[rpm]



(a) At 10,000[rpm]



(c) At 20,000[rpm]

Fig. 16. Experimental results of proposed motor with dynamometer

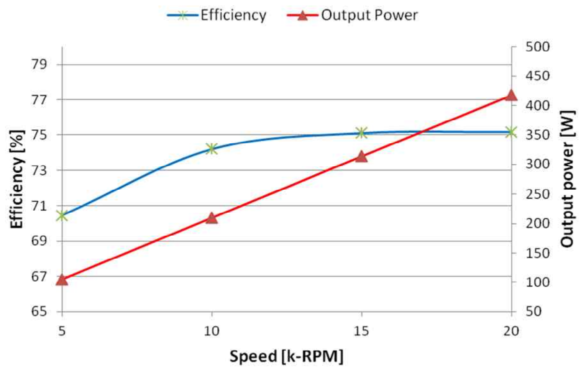


Fig. 17. Efficiency and output power characteristic at rated torque

shown in Fig. 17. The efficiency of the proposed motor is higher than that of the universal motor, which is 68%.

4. Conclusions

This paper presents a novel 2-phase 6/5 SRM which has short flux path to reduce core losses and increase torque production. In order to produce a continuous output torque, the positive torque region is extended with asymmetric inductance characteristic. The proposed motor is suitable for applications that require unidirectional rotation.

The performance of the proposed 6/5 SRM was verified with a practical drive system and air-blower test. In the experiment, the efficiency of the proposed motor is higher than that of the universal motor.

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