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분절회전자형 3상 SRM의 특성해석

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Characteristics Analysis of Segmental Rotor Type 3-Phase SRMs

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Abstract

In this study, two types of switched reluctance motors (SRMs) with segmental rotors are presented in detail. The first is a 6/5 segmental rotor type, whereas the second is a 12/8 segmental rotor type. Both motor types have the same stator, rotor, and winding configurations. The stator is constructed with special stator poles, namely, exclusively designed exciting and auxiliary poles. The rotor is constructed from a series of discrete segments, each of which is embedded into the nonmagnetic isolator. The windings are only wound on the exciting poles, and no winding is wound on the auxiliary poles. Given these configurations, short flux paths and high flux-linkage utilization rate are achieved in the proposed motors, which may reduce the magnetomotive force requirement and increase the electrical utilization of a machine. To verify the effectiveness of the proposed motors, their characteristics, such as magnetic flux distribution, flux-linkage, torque, radial force, and efficiency, are analyzed and compared with those of a conventional 12/8 SRM. Meanwhile, two prototypes, one for each proposed segmental rotor type, are also designed and manufactured. Finally, the validity of the proposed motors is further verified by test results.

Key words: Switched reluctance motor, Electric machines, Segmental rotor, Energy efficiency, Cooling fans

1. Introduction

Recently, switched reluctance motors (SRMs) have gained more attentions because of its advantage characteristics, such as good fault tolerance, simple structure, robustness, low cost and applicability in harsh environments[1]-[6]. In particularly, due to the development of the power electronics and higher and higher price of permanent magnets (PMs), SRMs have been treated as a powerful candidate for many aotomotive and aerospace products.

As is generally known, SRMs always employ double-salient poles and simple concentrated windings configurations, because of their simplicity and short end-windings. However, there have been developments using segmental rotor type SRMs[7]-[17] in the recent years to increase the electrical utilization of the machine, and thereby give much greater torque density than conventional SRMs.

In [7], a three-phase 12/8 segmental rotor type SRM is proposed and tested. Compared with conventional SRMs, this motor shows better torque per unit copper loss at thermal limit condition, but it has complex manufacturing and weak mechanical strength problems. To solve the above problems, a 6/4 segmental rotor type SRM is proposed[8]. In this motor, the rotor segments are embedded into an aluminum rotor block. This configuration not only makes the motor manufacture easier, but also increases the mechanical strength of the motor. Meanwhile, the advantages in the conventional 12/8 segmental rotor type SRM are also kept. To further improve the torque performance, the same structures of the segmental rotor type SRMs with increasing

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phase number, with 2-step slide rotor type are researched[9]-[10]. In addition, a circular slot segmental rotor type SRM[11] and an 8/6 bipolar segmental rotor type switched reluctance motor[12]-[13] are also proposed, respectively. However, all of these motors adopt full pitch windings. And the machines with full pitch windings have substantially longer end-winding, which reduces the electric loading and fault tolerant ability and also make them impractical for applications which combine a short lamination stack length with a large pole pitch[14]-[15].

Hence, based on the above analysis, a novel 6/5 segmental rotor type SRM with short flux path is proposed[16]-[17]. Unlike conventional segmental rotor type SRMs, this motor only has six stator poles and five rotor segments, and the stator poles are divided into exciting and auxiliary poles. Furthermore, in this motor the concentrated, short pitched windings are adopted and only wound on the exciting poles, resulting in the motor operating in short flux path. Therefore, compared with conventional segmental rotor types, this motor not only keeps the torque output capacity of conventional segmental rotor type SRMs, but also reduces the length of the end winding. However, due to the asymmetry of the inherent magnetic paths, the proposed 6/5 type encounters unbalanced force as the motor operates. To remove the unbalanced force, a novel 12/8 segmental rotor type SRM is proposed. The structure of the proposed 12/8 segmental rotor type is the same as that of the proposed 6/5 segmental rotor type except the number of the stator and rotor poles.

In this paper, the two types of the proposed SRMs, 6/5 segmental rotor type and 12/8 segmental rotor type, are analyzed by FEM and compared to conventional 12/8 SRM, including magnetic flux distribution, flux-linkage, torque, radial force. Meanwhile, the prototype of the proposed SRMs are also manufactured and tested. Finally, the experimental results are presented to verify the effectiveness of the proposed SRMs.

2. Two Novel SRMs with Segmental Rotor

2.1 Conventional 12/8 SRM

Fig. 1 shows a conventional 12/8 SRM with phase A windings. The windings on the stator poles P_{A1}, P_{A2}, P_{A3} and P_{A4} are connected in series. However, they can be connected in parallel. This depends on different application environments. For phase B and C, the winding connections are always the same as that of phase A. However, they are suited 30 and 60 mechanical degrees apart from phase A, respectively.

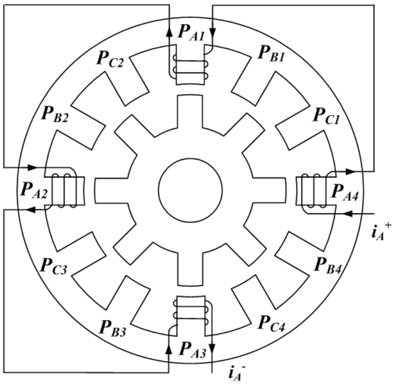
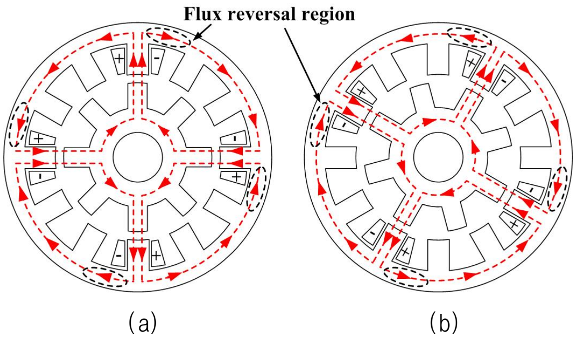


Fig. 1. Conventional 12/8 SRM with phase A windings.



(a) (b)

Fig. 2. Magnetic flux paths of conventional 12/8 SRM. (a) Phase A energized. (b) Phase B energized.

Fig. 2 shows the magnetic flux paths of the conventional 12/8 SRM. As shown in Fig. 2, the flux paths of this motor are long flux paths. Furthermore, there is flux reversal in the stator yoke when the phase current changes from one phase to another. For instance, assuming that the rotor of the conventional 12/8 SRM is rotating in a counter-clockwise direction, when the phase current is changed from phase A to B, there is flux reversal in the stator yoke as shown in Fig. 2. Similarly, the flux reversal may also appear as the phase current changes from phase B to C or from C to A. The flux reversal in the stator increases the stator core losses.

2.2 Proposed 6/5 Segmental Rotor Type SRM

Fig. 3 shows a novel 6/5 SRM with segmental rotor. Just as its name implies, the motor has six stator poles and five rotor poles. The stator poles are divided into two types. One is the exciting poles; the other is the auxiliary poles. The windings are only

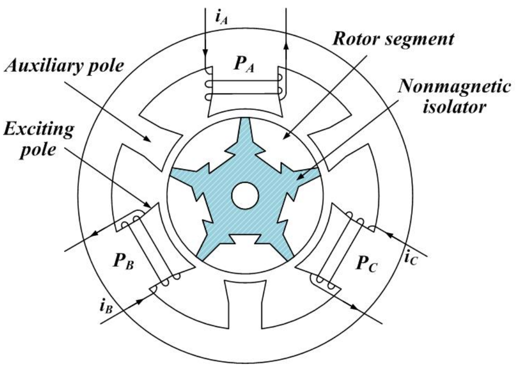
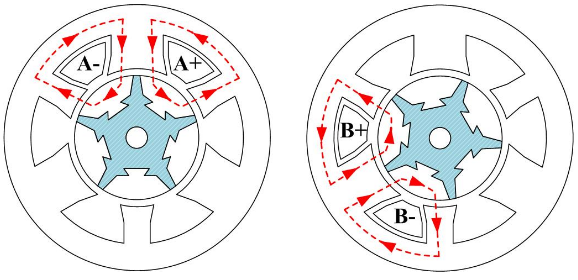


Fig. 3. Proposed 6/5 segmental rotor type SRM.



(a) (b)

Fig. 4. Magnetic flux paths of the proposed 6/5 SRM. (a) Phase A energized. (b) Phase B energized.

wound on the exciting poles and there are no windings on the auxiliary poles, so the auxiliary poles only act as the flux return paths. The rotor is comprised of series of discrete segments and nonmagnetic isolator. The rotor segments are embedded into the nonmagnetic isolator and magnetically isolated from each other segments.

Fig. 4 shows the magnetic flux paths of the proposed 6/5 SRM. As shown in the figure, the magnetic flux flows down from the wound stator poles and returns via the adjacent auxiliary poles, the flux paths are short. Moreover, when the phase current transits from phase A to B, there is no flux reversal in the stator of the proposed SRM. Likewise, the flux reversal does not exist with the phase current transition from phase B to C or from phase C to A. These features may increase the electrical utilization and decrease the magneto-motive force (MMF) requirement of the motor. However, as shown in Fig. 4, with one phase excited, the magnetic flux only flows on one side of the motor, which results in unbalanced force in the machine. As is well known, the unbalanced force may increase the acoustic noise and vibration of the machine as the motor operates.

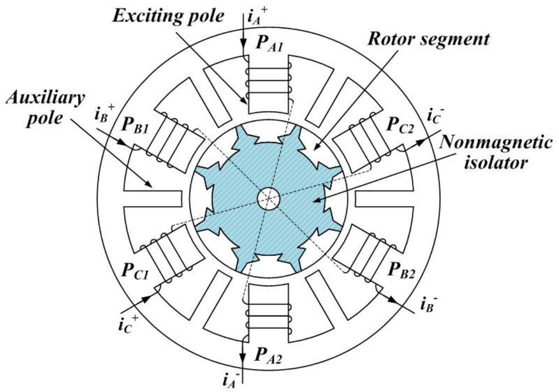
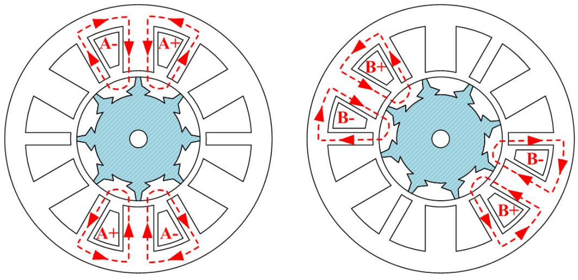


Fig. 5. Proposed 12/8 segmental rotor type SRM.



(a) (b)

Fig. 6. Magnetic flux paths of the proposed 12/8 SRM. (a) Phase A Energized. (b) Phase B Energized.

2.3 Proposed 12/8 Segmental Rotor Type SRM

In Fig. 5, a novel 12/8 segmental rotor type SRM is proposed. The structure is the same as that of the proposed 6/5 type except the number of the stator and rotor poles. The proposed motor is also a three-phase motor; to remove the unbalanced force, the windings on the diametrically opposite poles, such as the windings on the stator poles P_{A1} and P_{A2}, are connected in series to construct one phase.

Fig. 6 shows the magnetic flux paths of the proposed 12/8 type. As shown in Fig. 6, the magnetic flux flows down the wound stator poles and returns via the adjacent auxiliary poles on either side of the wound stator poles, which is the same as that of the proposed 6/5 type. However, the flux is symmetric in this motor. Hence, the proposed 12/8 type not only inherits the advantages of the proposed 6/5 type, but also has balanced radial force.

3. Characteristics Analysis of the Proposed SRMs with Segmental Rotor

To verify the proposed structures, the proposed 6/5

TABLE I
MACHINE DIMENSIONS

Parameter	Conventional 12/8 SRM (LFP[1])	Proposed 6/5 SRM (SFP[2])	Proposed 12/8 SRM (SFP)
Number of phase	3	3	3
Outer radius (mm)	52.5	52.5	52.5
Yoke thickness of stator (mm)	5	10	6
Outer radis of rotor (mm)	31	26	28
Length of air gap (mm)	0.25	0.25	0.25
Inner radius of rotor (mm)	24	-	-
Radius of shaft (mm)	4	4	4
Length of stack (mm)	35	35	35
Stator tooth width (mm)	7.6	20.5/10.5	14.6/5.9
Stator pole arc (deg.)	14	54/30	30/12
Rotor pole arc (deg.)	16	66	41
Number of turns/phase	20	12	16
Wire diameter (mm)	2.836	2.836	2.836
Slot fill factor	0.3	0.26	0.3
Resistance/phase (m Ω)	7.0	5.9	6.7

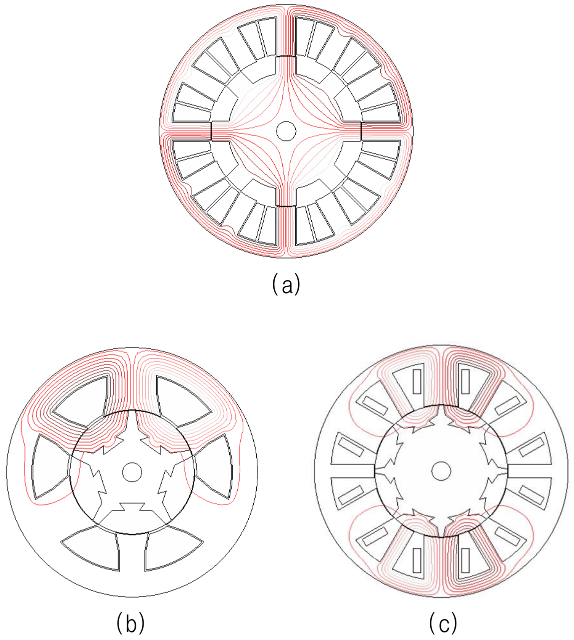
[1] Long Flux Path

[2] Short Flux Path

and 12/8 types are designed to compare with a conventional 12/8 SRM, which has been used for vehicle cooling fan. For accurate comparison between conventional 12/8 and proposed SRMs, both the proposed structures are deliberately made with exactly the same outside diameter, core axial length, air-gap and wire gauge as a previous constructed 12/8 motors. Meanwhile, the slot fill factor of the proposed types is kept lower than or same as that of the conventional 12/8 SRM. Furthermore, to satisfy the actual material requirement, the flux density in all three motors is designed to be lower than 1.8 Tesla. TABLE I gives the detailed parameters for all the three machines. To get the characteristics of all the three machines for comparison, finite element method (FEM) is employed.

3.1 Magnetic Flux Distribution

Fig. 7 (a) shows the magnetic flux distributions of the conventional 12/8 SRM with phase A excited at aligned positions. As shown in the figure, the magnetic flux flows into the rotor from the stator poles P_{A2} and P_{A4}, though the rotor and returns via the stator poles P_{A1} and P_{A3}. The flux paths are long flux paths.


(a)

(b) (c)

Fig. 7. Magnetic flux distributions of conventional 12/8 and proposed SRMs. (a) Conventional 12/8 SRM. (b) Proposed 6/5 SRM. (c) Proposed 12/8 SRM.

Fig. 7 (b) and (c) show the magnetic flux distributions of the proposed 6/5 and 12/8 types with phase A excited at aligned position. As shown in the figures, the magnetic flux flows down from the wound stator poles and returns via the adjacent auxiliary poles. All the conductors in each slot only couple with the flux driven by their own magneto-motive force with very little mutual coupling between one slot and another. Furthermore, the flux paths are short. However, the flux is asymmetric in the proposed 6/5 type, while it is symmetric in the proposed 12/8 type.

3.2 Flux-linkage, Torque and Force Characteristics

Fig. 8 shows the finite element predictions of the flux-linkage per turn for the conventional and proposed SRMs. As is generally known, the area enclosed between the aligned and unaligned curves is the change in coenergy, which corresponds to the energy converted to torque in a single stroke. From the above it is possible to derive the average torque per turn as,

$$T_{av} = \frac{\partial W'}{\partial \theta} = \frac{\partial \left(\int \Phi di \right)}{\partial \theta} \tag{1}$$

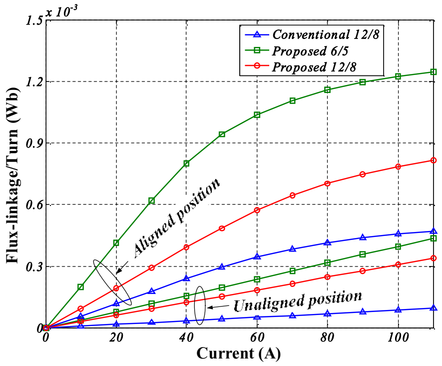


Fig. 8. Flux-linkage per turn.

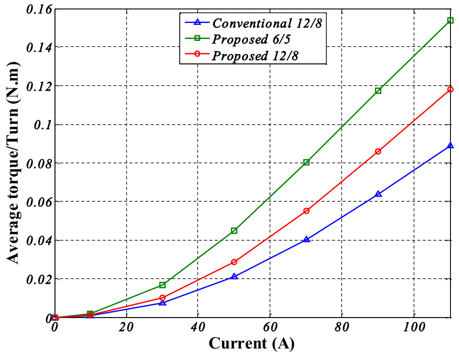


Fig. 9. Average torque per turn.

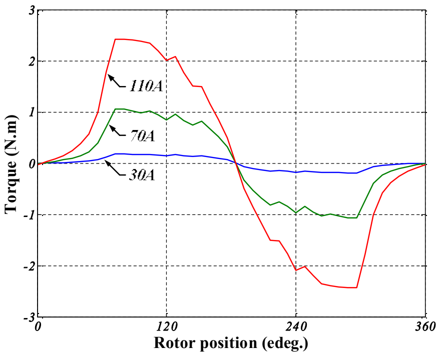


Fig. 10. Torque profiles of conventional 12/8 SRM.

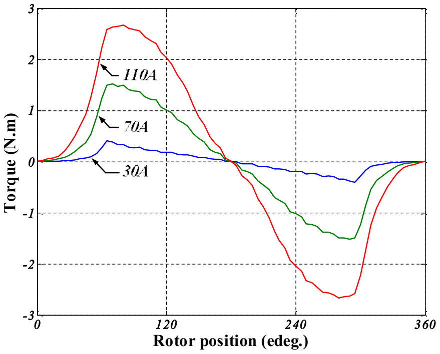


Fig. 11. Torque profiles of proposed 6/5 SRM.

Fig. 12. Torque profiles of proposed 12/8 SRM.

in which, T_{av} is the average torque per turn, W' is the coenergy, θ is the rotor position, Φ is the flux-linkage per turn, and i is the current. Then, the average torque of the motor can be calculated as,

$$T_{avm} = T_{av} \times N_{phase} \tag{2}$$

where, T_{avm} is the average torque of the motor, N_{phase} is number of turns per phase. Note that the number of turns per phase in the conventional 12/8 and proposed SRMs could be found in TABLE I.

Fig. 9 shows the average torque per turn for the conventional and proposed SRMs. As seen in Fig. 9, the average torque produced by the proposed types is higher than that of the conventional 12/8 type, especially for the 6/5 type, it is about two times that of conventional 12/8 type. Therefore, to produce the same torque, the proposed types require lower current or less winding turns. That is, compared with conventional 12/8 type, the MMF requirement is reduced and the electrical utilization of the machine is increased in the proposed types. This verifies the validity of the proposed SRMs.

Figs. 10, 11 and 12 show the torque profiles of the conventional 12/8 and proposed SRMs. The average torque comparison of all the three machines are shown in TABLE II. From TABLE II it can be found that the proposed SRMs can generate larger average torque than that of conventional 12/8 type at all current levels. However, the superiority becomes smaller and smaller with the current increased. This is because the proposed structures are easier to be saturated than that of the conventional 12/8 type.

Fig. 13 shows the radial force magnitude profiles of all the three machines with constant current 110A. Due to the asymmetry of inherent magnetic flux path,

TABLE II
AVERAGE TORQUE COMPARISON OF ALL THE THREE MACHINES (N.M)

Current	10A	30A	50A	70A	90A	110A
Torque of conventional 12/8 SRM	0.015	0.146	0.416	0.805	1.271	1.778
Torque of proposed 6/5 SRM	0.021	0.200	0.540	0.964	1.408	1.845
Torque of proposed 12/8 SRM	0.017	0.164	0.461	0.884	1.377	1.887

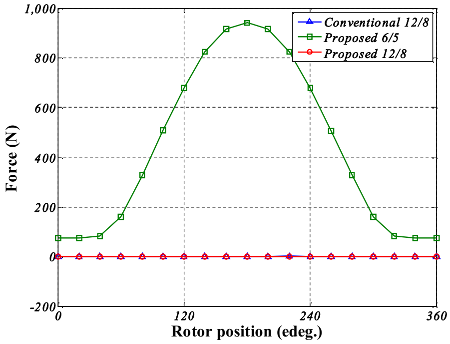


Fig. 13. Radial force profiles.

unbalanced force is produced in the proposed 6/5 type, while the force is very balanced in the conventional and proposed 12/8 SRMs. As is well known, the unbalanced radial force not only increases the acoustic noise and vibration of the machine, but also increases burden of the bearing, which may reduce the life of the bearing. For this reason, the 12/8 segmental rotor type SRM is researched even though the torque output capacity is lower than that of the proposed 6/5 type.

4. Experimental Results

To verify the validity of the proposed SRMs, prototypes of the proposed 6/5 and 12/8 structures are designed and manufactured, as shown in Fig. 14. Meanwhile, the rotor structure of conventional 12/8 SRM is also shown for comparison. Compared with the rotor structure of conventional 12/8 SRM, the segmental rotors do not have any mechanical saliency, and is slightly difficult to manufacture. The main dimensions of the prototypes are the same as that shown in TABLE I.

To verify the validity of the proposed types, experiments are performed to all the three machines. Fig. 15 shows the experimental platform. The experiments are realized by a Texas Instruments (TI) TMS320F28335 digital signal processor (DSP).

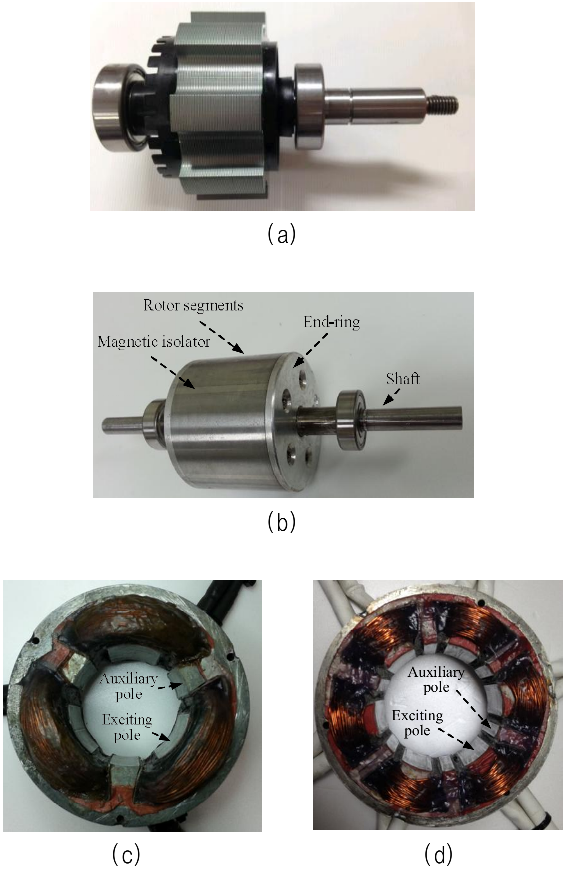


Fig. 14. Prototypes of all the three machines. (a) Rotor of conventional 12/8 SRM. (b) Rotor of proposed 6/5 type. (c) Stator of proposed 6/5 type. (d) Stator of proposed 12/8 type.

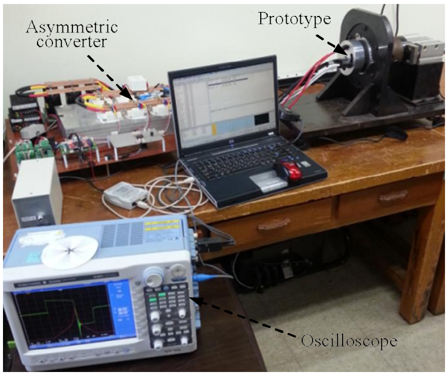


Fig. 15. Experimental platform.

Fig. 16 shows the comparison of the measured flux-linkage with those predicted using the three-dimensional (3D) finite elements. As shown in Fig. 16, the measured and predicted curves agree very well with the peak flux-linkage error lower than 2%

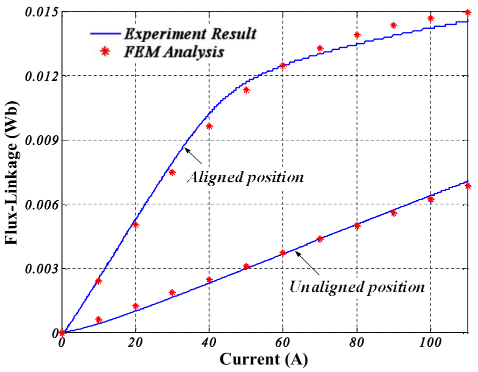


Fig. 16. Comparison between measured flux-linkage and those predicted using 3D finite elements.

and 5% at aligned and unaligned position, respectively. This error can be attributable to inexact B-H characteristics provided by the steel manufacturers, the leakage flux in the rotor magnetic isolator and nonuniformity of the air-gap.

Figs. 17 and 18 show the experimental results of the proposed SRMs as the motors operate at rated load condition, 1.7 N.m and 2800 rpm. In the experiment, PWM control method is used to control the motor at low speed, and angular position control method is used at high speed. From the figures, it can be seen that the phase current has an upwarp at the end of the conduction cycle. This is caused by the saturation of the core. It can be reduced or even removed by regulating the turn on and off angles. However, the current with a little upwarp at this position may make the motor high efficiency.

TABLE III shows the performance of all the three machines at rated condition. The proposed SRMs have higher efficiency than that of conventional 12/8 SRM. And the proposed 12/8 type has the best efficiency. However, it should be noted that the current in the proposed 6/5 SRM is higher than that of the conventional 12/8 SRM. There are two main reasons.

Firstly, the proposed 6/5 SRM is designed with the windings as few as possible for reducing the motor cost as the motor produces enough torque to satisfy the rated load requirement. It can be seen from TABLE I that the turn number per phase, slot fill factor and phase resistance of the proposed 6/5 SRM is lower than that of the other two types.

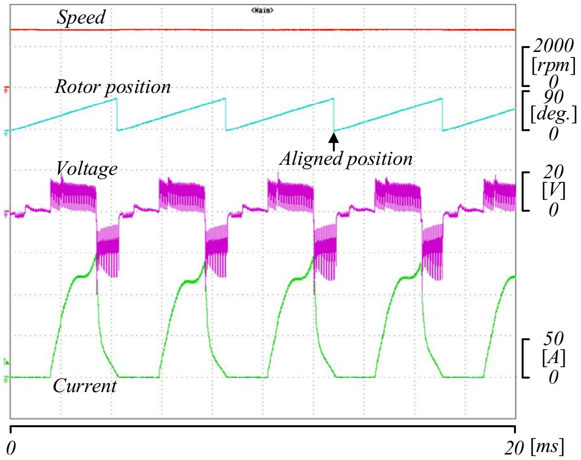


Fig. 17. Experimental results of the proposed 6/5 SRM at rated condition.

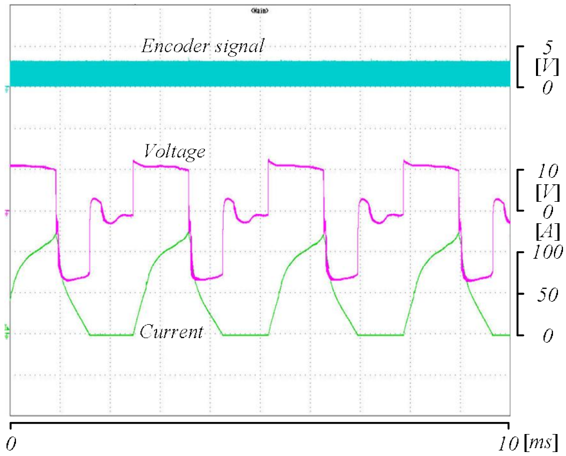


Fig. 18. Experimental results of the proposed 12/8 SRM at rated condition.

TABLE Ⅲ
PERFORMANCE COMPARISON

Parameter	Conventional 12/8 SRM	Proposed 6/5 SRM	Proposed 12/8 SRM
Rated speed (rpm)	2800	2800	2800
Rated torque (N.m)	1.7	1.7	1.7
Phase current in RMS (A)	64.9	73.0	62.9
Output power (W)	498.10	498.47	499.05
Input power (W)	636.14	633.40	623.34
Efficiency (%)	78.3	78.7	80.1

Secondly, the proposed 6/5 SRM is affected by the cross-saturation. As is well known two phases are always excited at the same time in an SRM during the commutation region. When two phases are excited together, the flux paths in the proposed 6/5 SRM are shown in Fig. 19. As shown in Fig. 19, each portion of the stator yoke and each exciting pole only carry the flux of one phase, only the auxiliary poles, providing the flux return path, contain the flux of two phases. However, the auxiliary poles of the proposed 6/5 SRM have been dimensioned to only take the flux

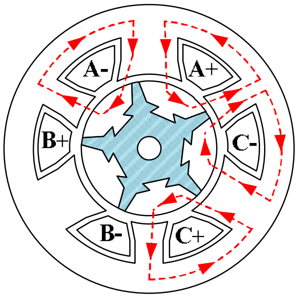


Fig. 19. Magnetic flux paths of the proposed 6/5 SRM with two phases excited simultaneously.

of a single-phase, and hence there is the possibility of cross-saturation in the auxiliary poles, which reduces the torque. The cross-saturation always occurs when the machine is operating under angular position control and positive voltage is applied for more than one-third of a cycle. For the proposed 6/5 SRM, with the motor operating at rated condition, the dwell angle of the proposed SRM is 32°, which is more than 24°, one-third of a cycle. Therefore, the proposed motor is affected by cross-saturation, thereby resulting in higher current to generate the same torque than that of conventional 12/8 SRM.

5. Conclusions

In this paper, two segmental rotor type SRMs are presented and compared with a conventional 12/8 SRM. Both the static analysis and the test results are presented. From the analysis, it can be concluded that the proposed SRMs has better torque output capacity than the conventional 12/8 SRM, and the turn number in the 6/5 and 12/8 segmental rotor type SRMs is reduced by 40% and 20%, respectively. However, the proposed 6/5 SRM encounters the effect of the unbalanced radial force. From the experimental results, it can be seen that the static performance got by the experiments has a good match with that predicated by 3D FEM. Furthermore, the proposed SRMs have better efficiency than that of conventional 12/8 SRM, which verifies the validity of the proposed structures.

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