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Design and Analysis of a Segmental Rotor Type 12/8 Switched Reluctance Motor

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Abstract

In this paper, a novel 12/8 segmental rotor type switched reluctance motor (SRM) is proposed for cooling fan applications. Unlike conventional structures, the rotor of the proposed structure is constructed from a series of discrete segments, and the stator is constructed from two types of stator poles: exciting and auxiliary poles. Moreover, in this structure, short flux paths are taken and no flux reversion exists in the stator. While the auxiliary poles are not wound by the windings, which only provide the flux return path. When compared with the conventional SRM, the proposed structure increases the electrical utilization of the machine and decreases the core losses, which may lead to a higher efficiency. To verify the proposed structure, the finite element method (FEM) and Matlab-Simulink are employed to get the static and dynamic characteristics of the proposed SRM. Finally, a prototype of the proposed motor was tested for characteristic comparisons.

Key words: High efficiency, Segmental rotor, Short flux path, Switched Reluctance Motor (SRM)

I. INTRODUCTION

A Switched Reluctance Motor (SRM) is a doubly-salient and singly-excited machine wherein the stator carries the wingding and the rotor is simply made of stacked silicon steel laminations. When compared with other types of motors, the SRM has several advantages, such as: less maintenance, higher fault tolerance, rugged construction, no permanent magnet, simple structure and a very wide range of speeds [1]-[4]. Furthermore, the SRM has several outstanding characteristics, such as good reliability and lower hysteresis loss [2]-[6]. With these advantages, the SRM has gained more attention recently and has been treated as a good alternative for electric motor drive applications.

However, the SRM also possesses several disadvantages, such as torque ripples, which are produced in the SRM because of its operation principle and magnetic structure. The torque ripples in the SRM contribute to mechanical wear and acoustic noise. These torque ripples can be reduced, and the performance of the SRM can be improved by modifying the geometry or by using an appropriate control method [7]. An optimal control method to reduce the torque ripple is not discussed in this paper.

Nowadays, full pitch windings are used in SRMs to increase the electrical utilization of the machine, which improves the torque capability at the expense of an increased end-winding length [8]-[13].

In this paper, a novel 12/8 segmental type SRM with a short flux path and no flux reversed in the stator is proposed [14]. Unlike the conventional structures, the rotor of the proposed structure is constructed from a series of discrete segments and the stator is constructed from two types of stator poles: exciting and auxiliary poles, in which the segmental core is embedded in an aluminum (conductive metal) rotor block in order to increase the mechanical strength and the ease of manufacturing as well as to improve the torque performance. When compared with the conventional SRM, the proposed structure increases the electrical utilization of the machine, and decreases both the magneto-motive force (MMF) requirements and the core losses. All of the characteristics of the proposed 12/8 segmental rotor type SRM are analyzed by FEM and Matlab-Simulink.

II. DESIGN OF THE SEGMENTAL ROTOR TYPE SRM

This section presents the basic principles of the novel 12/8 segmental rotor type SRM with a short magnetic flux.

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TABLE I
SPECIFICATIONS OF THE PROPOSED SRM

Parameters	Value	Parameters	Value
Output Power	500[W]	Average Torque	2.011[Nm]
Stator Poles	12	Rotor Poles	8
Outer Radius	52.5[mm]	Outer Radius of Rotor	28[mm]
Length of Stack	35[mm]	Air-gap	0.30[mm]
Stator Pole Arc	30/12[°]	Rotor Pole Arc	41[°]

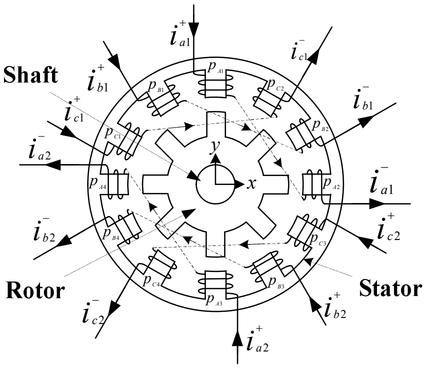


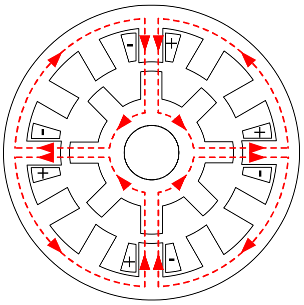
Fig. 1. Conventional 12/8 SRM.

Furthermore, FEA analyses of the proposed motor are also presented. In order to show the advantages of the proposed motor, a comparison of the torque of the conventional 12/8 and the proposed SRM is presented. Table I shows the specifications of the proposed SRM.

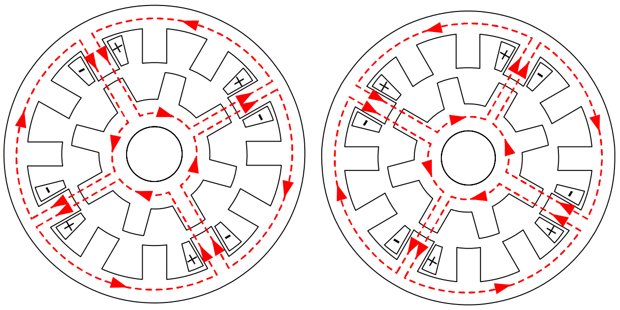
A. Conventional 12/8 SRM

Fig. 1 shows a typical structure for a conventional 3-phase 12/8 SRM with Phase A at the aligned position. As shown in this figure, at this position, either the rotor will rotate in the clockwise direction when Phase B is excited or the rotor will rotate in the counterclockwise direction when Phase C is excited. Therefore, the rotor can rotate clockwise or counterclockwise depending on the excitation sequence.

Fig. 2 Shows the magnetic flux path of the 12/8 SRM with the rotor rotating in the counterclockwise direction. In Fig. 2, when the rotor is rotating in the counterclockwise direction, "-" stands for the current flow into the paper, and "+" stands for the current flow out of the paper. When the phase current changes from Phase A to Phase B, it has a one third flux reversal in the stator yoke and a one half flux reversal in the rotor yoke. This phenomenon is the same when the phase current changes from Phase B to Phase C. Therefore, the core loss is almost same in these two commutation regions. However, when the phase current changes from Phase C to Phase A, it is a little different from the current changing from Phase A to Phase B, or from Phase B to Phase C. In this case, there will be a two thirds flux reversal in the stator yoke and a one half flux reversal in the rotor yoke. Because the length of flux reversal path is increased, the core loss is also increased in this commutation region when compared with the other two commutation regions. In order to increases the electrical utilization of the machine and to decreases the core losses, a novel 12/8 segmental rotor type SRM is proposed in this paper.



(a) Phase A excited.



(b) Phase B excited. (c) Phase C excited.

Fig. 2. Magnetic flux path of 12/8 SRM with rotor rotating at counter-clock direction.

B. Novel 12/8 Segmental Rotor Type SRM

The concept of the proposed motor is based on the conventional 12/8 3-phase SRM. The 12/8 SRM employs a long magnetic flux path. This magnetic path is related to the core loss of a motor. A short magnetic path is better than a long ones to reduce mmfs. To realize a short magnetic path in a 3-phase motor, the stator-rotor poles of a 12/8 motor have to be modified. The stator pole should be able to stream the magnetic flux through the shortest path, while the rotor poles should be able to drain the magnetic flux in any rotor position.

This modified structure makes the conventional 12/8 SRM into a 12/8 segmental rotor type SRM with a short flux path and no flux reversion in the stator. The concept of the proposed 3-phase 12/8 segmental rotor type SRM is presented in Fig. 3.

Unlike conventional structures, the rotor is constructed from a series of discrete segments. Each rotor is embedded in an aluminum rotor block and magnetically isolated from its neighbors. From Fig. 3, it can be seen that the stator has two types of stator poles: exciting and auxiliary poles. The exciting poles are wound by the windings, while the auxiliary poles are not wound by the windings, and only provide the flux return path. The windings on the exciting poles PA1 and PA2 are connected in series to construct Phase A, the windings on the exciting poles PB1 and PB2 are connected in series to construct Phase B, and the windings on the exciting poles PC1 and PC2 are connected in series to construct Phase C.

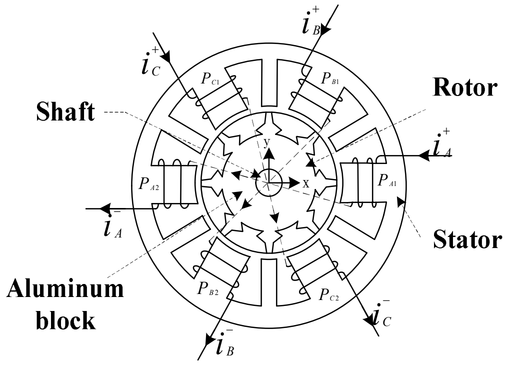
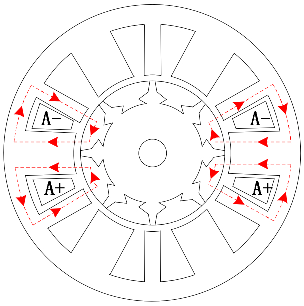
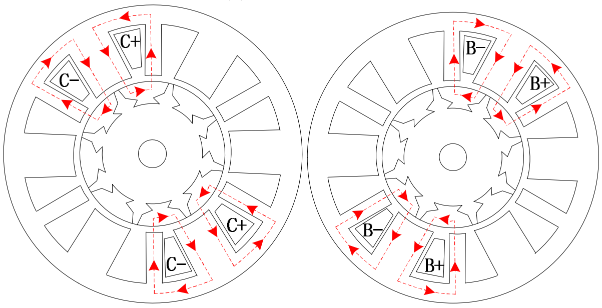


Fig. 3. 12/8 segmental rotor type SRM.



(a) Phase A excited

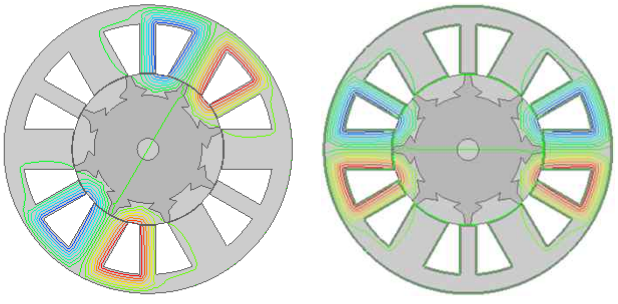


(b) Phase B excited (c) Phase C excited

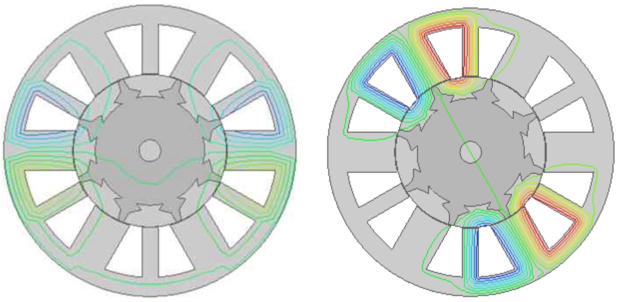
Fig. 4. Magnetic flux path in proposed SRM.

A short magnetic flux path can be achieved by incorporating one exciting and two adjacent auxiliary poles into one magnetic circuit. This flux configuration needs a different winding arrangement. The winding arrangement of the proposed motor is shown in Fig. 3. The advantages of a short magnetic flux are the ability to increase the efficiency and torque production while decreasing the core loss.

Fig. 4(a) shows the magnetic paths of the proposed structure when phase A is excited at the aligned position. The magnetic paths of the proposed structure with Phase B and Phase C energized are shown in Fig. 4(b) and (c), respectively. As shown in the figure, the magnetic flux flows down from the exiting pole, through the rotor segments and returns via the adjacent auxiliary poles. All of the conductors in each slot only couple with the flux driven by their own magneto-motive force (MMF) with very little mutual coupling between one slot and another. This increases the electrical utilization of the machine and decreases the MMF requirement. Meanwhile, in the proposed structure short flux paths are taken and no flux reversal exists in the stator core, which can lead to lower core losses.



(a) Phase A. (b) Phase B.



(c) Phase C. (d) un-aligned rotor position.

Fig. 5. Magnetic flux distribution.

C. FEA Analyses

An electromagnetic 2-dimensional (2D) FEA is performed in the conduction region for a 110-Ampere excitation current (full-load), and the magnetic flux distribution is analyzed. Fig. 5 shows the magnetic flux distribution of the proposed SRM. Figs. 5(a) to 5(c) show the magnetic fluxes of Phase A, Phase B and Phase C at the aligned position, respectively. In addition, Fig. 5(d) shows flux distribution at an unaligned rotor position. From the figures, it can be seen that all of the conductors in each slot only couple with the flux driven by their own magneto-motive force (MMF), with very little mutual coupling between one slot and another. Moreover, in the proposed structure short flux paths are taken and no flux reversion exists in the stator core, which coincide with the concept of the proposed structure.

An SRM is normally designed to operate in the saturated-energy region. The torque of an SRM is produced by the attraction of the rotor poles to the excited stator phase, according to the reluctance principle. The torque produced by an SRM is independent of the polarity of the phase current. When a stator phase is energized, the nearest rotor-pole pair is attracted toward the energized stator in order to minimize the reluctance of the magnetic path. In this condition a positive torque is produced. The torque (T) of an SRM, which is related to the rotor position (θ) and phase current (i), can be expressed as:

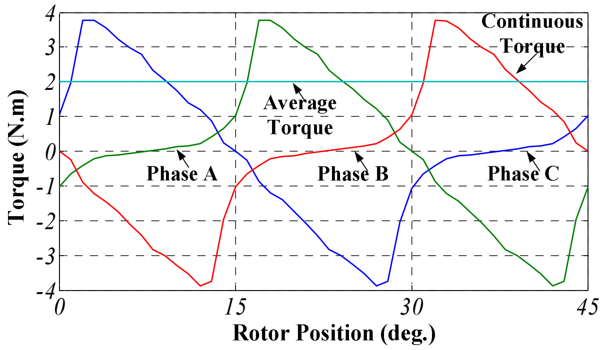


Fig. 6. Continuous torque.

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

By using the 2D FEA, the inductance and torque characteristics are analyzed. The electromagnetic behavior of each motor phase is commonly analyzed independently, since the magnetic interactions between phases are typically very small for conventional motors and can be ignored for the sake of simplicity. However, in this case, in order to analyze the average torque, the continuous torque of the proposed SRM is required. Fig. 6 shows the continuous torque of the proposed 12/8 segmental rotor type SRM.

From Fig. 6, it can be seen that the maximum torque produced by 110A-excitation current is 3.91 Newton-meters (Nm). The continuous torque is based on the neutral commutation angle (22.5 mechanical degrees), with no over-lap among the phases. However, to achieve a low torque ripple, there is usually an overlap between the phases. In the overlapping region, both phases contribute torque production to the machine. The torque ripple can be optimized by regulating the turn on and turn off angles to make the motor torque ripple lower. The optimal control method to reduce the torque ripple is not discussed in this paper. The average torque produced by the proposed SRM without an overlap angle is 2.011Nm.

The inductance profile has a considerable effect on motor operation and is also related to torque production. The aligned position of a phase is defined as the orientation when the stator and rotor poles of the phase are fully aligned, attaining the minimum reluctance position. The phase inductance is maximized in this position. Phase inductance decreases gradually as the rotor poles move away from the aligned position in either direction. When the rotor poles are symmetrically misaligned with the stator poles of a phase, the position is said to be in the unaligned position, and the inductance is minimized in this position.

In most SRM applications, saturation results in a nonlinear inductance. Since the proposed SRM has eight rotor poles, a rotation of 22.5° from alignment to nonalignment is sufficient to obtain the inductance profile characteristic of one electrical cycle. The initial rotor position is in the full-aligned position and the rotor rotates in the counterclockwise direction. In the case of the aligned stator-rotor position (0° and 45°), the inductance is at its highest and the magnetic reluctance of the flux is at its lowest. The inductance curves with respect to the rotor position are shown in Fig. 7.

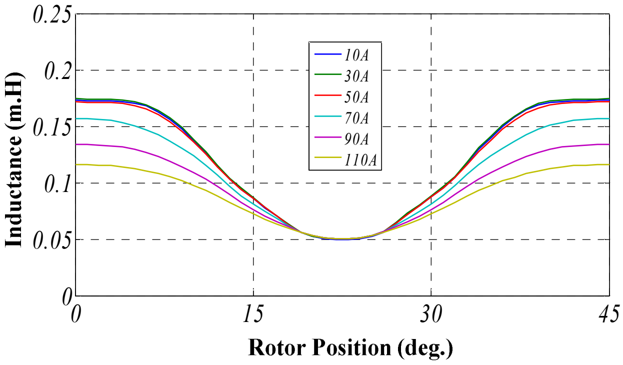


Fig. 7. Inductance profile.

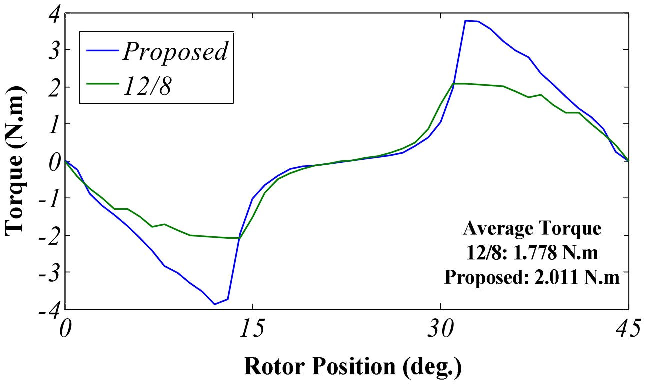


Fig. 8. Torque characteristics.

Fig. 8 shows a torque comparison of the conventional 12/8 and the proposed SRM. Both the conventional 12/8 and the proposed SRMs use the same dimensions and input parameters.

As shown in Fig. 8, the average torque of the conventional 12/8 SRM is 1.778[Nm], while that of proposed SRM is 2.011[Nm]. The average torque of the proposed SRM is 13.1% higher than that the conventional SRM.

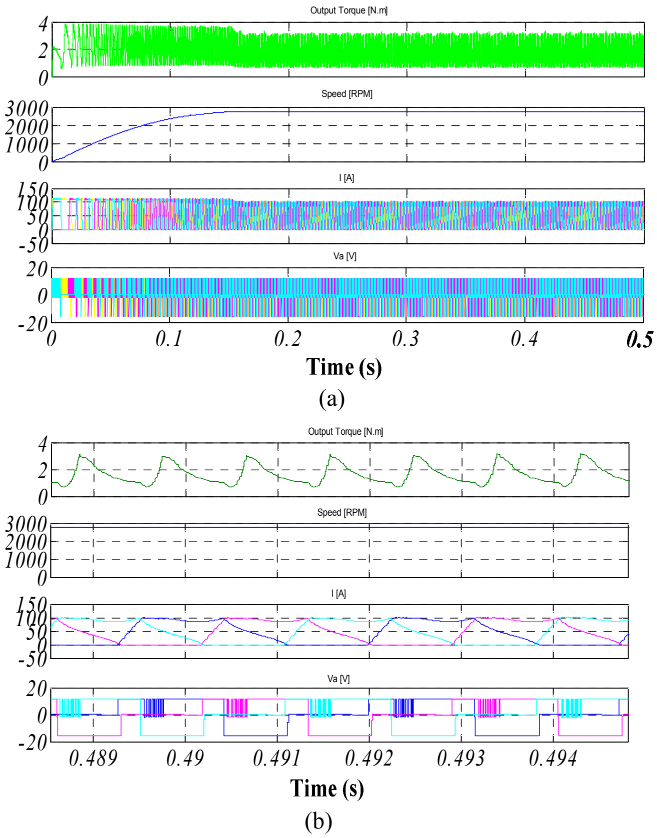
III. SIMULATION OF THE PROPOSED MOTOR

After the proposed motor was analyzed by the FEA software, the full torque and inductance were analyzed. 2D look-up tables of the current verse rotor position and flux linkage, and of the torque verse rotor position and current were used for the simulation.

The relationship between the voltage, resistance and inductance of the SRM is given by (2).

$$v = R_s i + \frac{d\lambda(\theta,i)}{dt} \tag{2}$$

where R_s is the phase resistance, v is the voltage applied across the phase winding, and $\lambda(\theta,i)$ is the phase flux



(a)

(b)

Fig. 9. Simulation results.

linkages depending on the rotor position and excited current.

The voltage drop of the SRM can be determined by using the phase flux linkage data and phase resistance. The speed of the SRM can be determined by using the load equation. The load for the simulation consists of inertia, friction, and load torque. The load equation is given by (3).

$$J\frac{d\omega_m}{dt}+B\omega_m=T_e+T_l \tag{3}$$

where J is the combined moment of inertia of the motor and load, B is the combined friction coefficient of the motor and load, and T_l is load torque.

From (3) the speed of the SRM is determined by (4).

$$\omega_m=\int\frac{T_e-T_l-B\omega_m}{J}dt \tag{4}$$

The number of turns per stator pole is only one in the FEA analysis. After that, the number of turns is determined by observing the tail of the current when it is turned off. A high turn number results in a low current/torque ratio and a long tail of the current and vice versa. A low current/torque ratio is a good index of performance whereas a long tail of the current produces a negative torque. To balance these two things, 8 turns/pole is selected.

As shown in Fig. 9(a), the speed rising time is about 0.15s. It is fast enough for the system response. The speed rising time depends on the unaligned inductance, the current slope, and the system inertia moment. A lower unaligned inductance results in a lower speed rising time while the rated current and voltage are kept constant. In order to reduce the unaligned inductance, the turn number of the windings can be reduced while increasing of the excited current, and keeping the mmf constant.

Fig. 9(b) shows simulation results for the proposed SRM after adjusting the zoom. In this simulation, the operational parameters are the same as the real system. The proposed motor is operated at 2800 rpm with 12Vdc, 102 A.

Table II shows the speed-torque and speed-efficiency of the proposed SRM, and Fig. 10 shows speed-torque and speed-efficiency comparisons of the 12/8 and the proposed types. From the comparison results, it can be seen that the proposed structure improves the electrical utilization of the machine and reduces the core loss, which reaffirms the novelty and advantages of proposed structure.

TABLE II

SPEED-TORQUE AND SPEED-EFFICIENCY OF THE PROPOSED SRM

Speed(rpm)	2600	2800	3000	3200	3400	3600
Torque(N.m)	1.70	1.70	1.59	1.49	1.40	1.30
Efficiency(%)	81.85	83.35	84.09	84.15	84.27	84.76

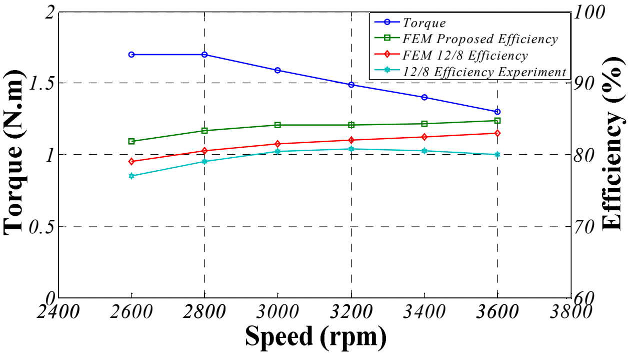


Fig. 10. Efficiency comparisons of 12/8 and proposed SRMs.

IV. EXPERIMENTS OF THE STATIC PERFORMANCE

In order to verify the validity of the proposed structure, a prototype of the proposed 12/8 SRM is designed and manufactured, as shown in Fig. 11. The stator and rotor lamination of the designed machine are S18. The materials of the rotor block and shaft are BS2 grade and S45C grade, respectively. The main specifications of the prototype motor are shown in Table I.

The prototype machine has been subjected to static performance testing. Fig. 12 shows the experimental platform. As shown in Fig. 12, the machine has been coupled with a dynamometer and driven by a three-phase asymmetric inverter. The experiments are realized by a Texas Instruments (TI) TMS320F28335 digital signal processor (DSP).

(a) stator (b) rotor.

Fig. 11. Prototype of proposed SRM.

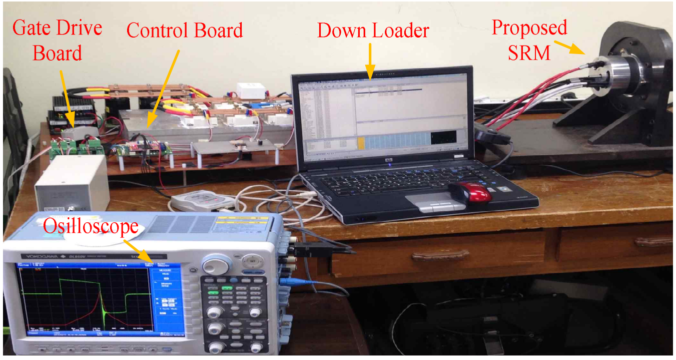


Fig. 12. Experiment platform.

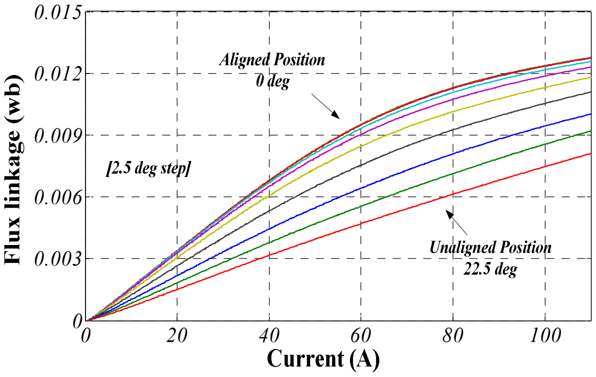


Fig. 13. Measured flux-linkage curves.

For the constant sampling time, the flux-linkage can be as:

$$\varphi_{k+1} = \varphi_k + (V - iR)\Delta t \tag{5}$$

Where φ is the flux-linkage, V and i are the measured phase voltage and current, R is the phase resistance, and Δt is the sampling time.

Fig. 13 shows the results of the tests for a series of positions, ranging from the unaligned to aligned positions. For the proposed 12/8 structure, there is 45 degrees of one rotor pith. The phase inductance depends on the flux-linkage and current, with 22.5 degrees of half of the rotor pith from the aligned to the unaligned position. A comparison is shown in Fig. 12.

Fig. 14 compares the actual measurements with those predicted using the two-dimensional finite elements. The measured and predicted curves for the aligned position are within 1% of the peak flux-linkage. However, the predicted unaligned flux-linkage is 15% less than the measured value. The large error at unaligned position is mainly caused by the end-winding leakage inductance, which is not considered in the predicted values. Furthermore, this leakage component is also present in the aligned position. However, its influence is reduced due to the saturation of the machine core.

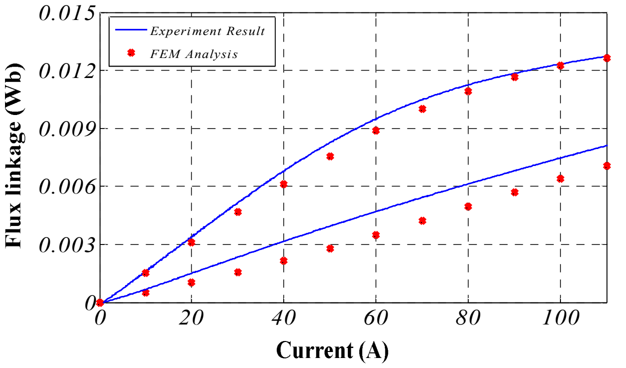


Fig. 14. Comparison between measured and FEA flux-linkage.

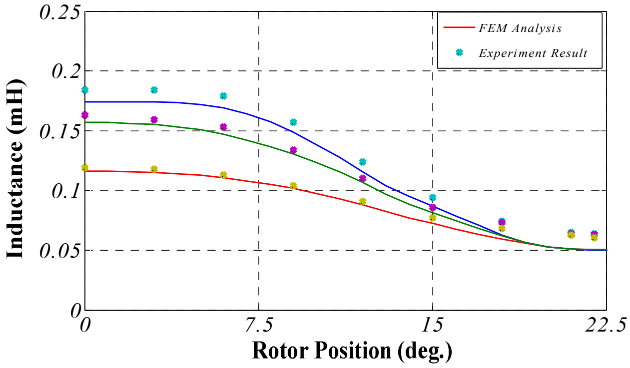


Fig. 15. Comparison of measured and FEA inductance.

The inductance can be derived directly from the flux-linkage as:

$$L(t) = \frac{1}{i(t)}\left\{\lambda(0) + \int_0^t \{v(t) - R_s i(t)\}dt\right\} \tag{6}$$

Fig. 15 shows comparisons with the measured values for three different excitation levels. As shown in Fig. 13, the agreement between the predicated and the measured values is very good, with the predicted inductance having the correct shape of the inductance profile. However, at the unaligned position for all of the current levels or at the aligned position with a low exciting current, the measured inductance value is somewhat higher than those predicted. This is mainly caused by the end-winding leakage inductance, as discussed above.

V. CONCLUSIONS

In this paper, a novel 12/8 segmental rotor type SRM is proposed. In this structure, short flux paths are taken and no flux reversion exists in the stator. Characteristics, including static and dynamic, are analyzed. A torque comparison between the proposed and a conventional 12/8 SRM is also executed, which demonstrates that the proposed SRM offers better performance in term of maximum and average torque production. The comparison and experimental results verify the validity of the proposed structure. More detailed experimental results and performance evaluations will be published in a future paper.

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