

A Novel Switched Reluctance Motor with U-type Segmental Rotor Pairs: Design, Analysis and Simulation Results

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Abstract—This paper describes the design and modeling procedure of a novel 5-phase segment type switched reluctance motor (ST-SRM) under simultaneous two-phase (bipolar) excitation of windings. The rotor cores of ST-SRM are embedded in an aluminum block as well as to improve the performance characteristics. The magnetic circuit of the produced ST-SRM is constructed so that the magnetic flux paths are short and exclusive to each phase, thereby minimizing the commutation switching and eddy current losses in the laminations. The design and simulation principles presented apply primarily to conventional SRM and ST-SRM. It is proved that the novel 5-phase switched reluctance motor under two-phase excitation is superior among the criteria used in comparison. The purposed model is particularly well suited for high torque and weight constrained applications such as automobiles, aerospace and military applications.

Keywords—Segmental Rotor Pairs, Two-phase Excitation, Commutation Switching, Aluminum Block.

I. INTRODUCTION

SWITCHED Reluctance Motors have received a considerable attention throughout the industrial environment because of rapid developments in semi-conductors such as IGBTs and MOSFETs. The term “SRM” relates to a motor which has two sets of salient poles. The coils in the stator are arranged in phases of one or more that must be energized individually or together to facilitate shaft rotation which produces torque, either the stator is a part of out-runner or in-runner SR machine.

The novel five-phase SRM of the type described herein includes a stator having evenly spaced salient poles and a rotor having segmental U-type cores which are embedded in aluminum block so as to increase mechanical strength. In the motor, two adjacent phases must be energized at all times to create short flux loops and provide controlled rotor rotation. The ST-SRM having foregoing structure and phase excitation scheme substantially provides a greater output torque than a same-sized conventional SR motor. The performance characteristics of the produced motor are investigated by finite element method (FEM). Eventually, the maximum torque of

novel five-phase ST-SRM is increased 2.03 times more in comparison with conventional SRM of the same size and furthermore a smoother torque and output power profile is obtained.

II. FIVE-PHASE NOVEL SEGMENT TYPE SRM

A. Motor Structure and Construction Procedure

Fig. 1 shows the CAD design of our produced segment type SRM with 10 stator poles with phase coils and 4 U-type rotor cores which have been embedded in aluminum rotor block. The design parameters of the motor have been calculated as in [1]-[3]. Some of the parameters calculated by using equations have been optimized to obtain better flux, inductance and torque profiles by FEM. Fig. 2 shows the photos of the stator and rotor cores of novel ST-SRM design.

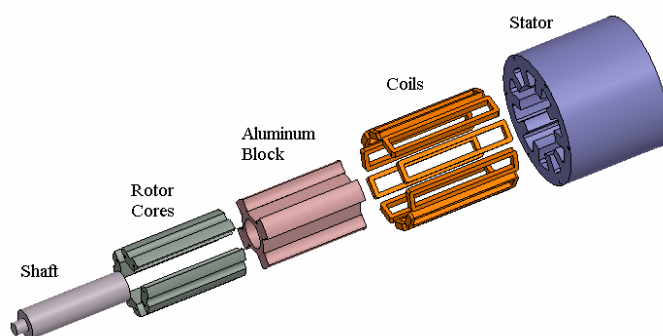


Fig. 1 CAD model of the motor



(a) Front views of the stator and rotor before they are joined to other parts and placed into frame

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(b) Prototype ST-SRM assembly

Fig. 2 Photos of ST-SRM

TABLE I
 CALCULATED AND OPTIMISED DESIGN PARAMETERS

No	Design Parameter	Design Value
1	Number of phases	5
2	Stator/rotor configuration	10/8
3	Stator outer diameter	150 mm
4	Rotor outer diameter	79.4 mm
5	Stack length	120 mm
6	Air gap length	0.3 mm
7	Stator pole arc	0.314 rad
8	Rotor pole arc	0.331 rad
9	Number of turns per phase	100
10	Stator/rotor construction material	M530-50A silicon steel (0.5 mm thickness)
11	Copper wire diameter	1.25 mm

Motor construction procedure can be explained as follows:

- The novel 5-phase motor laminations of M530-50A silicon steel sheets were cut by a designed mold pattern.
- A stacking fixture was made to stack pre-cut stator and rotor core laminations and a stacking factor of 0.945 was achieved.
- Fifty turns of 1.25 mm diameter copper wire were wound around each stator pole and eventually a stator slot fill factor of %42 was achieved. So, the number of turns per phase is 100. Each phase consists of two coils group as indicated in Fig. 3 and Fig. 4.
- The aluminum block used in the rotor to increase mechanical strength was processed in CNC bench. The small rotor laminations were stacked on aluminum block and the aluminum block was located on the shaft key.
- And in the end, a ST-SRM motor which has a maximum output power of 1.2kW.

All specifications belonging to novel five phase ST-SRM are listed in Table 1.

B. The Merits of Novel Design

As compared to conventional SRM designs, the novel ST-SRM has many additional features that can be summarized as follows:

- The simultaneous excitation of two phases at all times results in pairs of adjacent stator poles being magnetized with opposite polarity, thereby forming a magnetic circuit of which path includes only the portion of the yoke bridging the two adjacent stator poles of a pair.
- The produced ST-SRM significantly reduces the

hysteresis and eddy current losses experienced in back iron because of the fact that the motor phases are using short flux loops all the time.

- Another specific object of the motor is to provide high torque having small torque ripple characteristics and no dead torque position for the rotor. Eventually, efficiency of the motor is increased.
- In the middle area of all rotor cores, there is a gap along the stack length of the motor. This gap is left to help the motor to be cooled better.
- The secondary magnetic circuits causing flux switching frequency are eliminated with this novel design. Because, relative polarities of simultaneously polarized pairs are maintained such that neighboring poles separated by de-energized pairs of poles are of the same polarity.

C. ST-SRM's Operation Principle

In order to achieve a full rotation of the 5-phase motor, the windings must be energized in the correct sequence. For example, when A (A1 and A2 coils) and B (B1 and B2 coils) phases are excited according to the excitation scheme indicated in Fig. 4, the rotor will align itself with these poles. This will cause a rotation of 18° in clock wise direction.

One of the most important points of the operation is that the poles should be energized or de-energized before the rotor poles align themselves with the relevant stator poles. In our application, the phases are energized or de-energized 4.5° before the rotor poles reach to aligned position.

This sequence continues through C-D, E-A, B-C and D-E phases respectively and the excitation sequence will cause the flux to circumrotate in clock-wise. At the same time, the rotor will rotate in counter-clock-wise direction of 90°.

III. SYSTEM, SIMULATIONS AND RESULTS

A. Power Converter and Control System Design

It must be noted that the application of simulation method for novel 5-phase ST-SRM calls for a bipolar converter topology as shown in Fig. 3. Since unipolar converters are traditionally used for the control of the SRMs, one may question the additional cost introduced in using an H-bridge for each phase of the machine. The research shows that for current intensive automotive applications where the use of high current MOSFET switches are common, the difference in cost for semiconductor components including their support electronics are very minor and well justified for the improvement in efficiency [4]. In a circuit like this, it must be emphasized how to drive high and low-side MOSFETs at the same time. In simulations there is not any need to control this action but in real applications it must be chosen to use either a high/low side MOSFET or a different power source. The designed five-phase converter circuit has 20 MOSFETs and is used not only for 2, 3, 4 and 5 phase bipolar drive tests and also unipolar drive-tests.

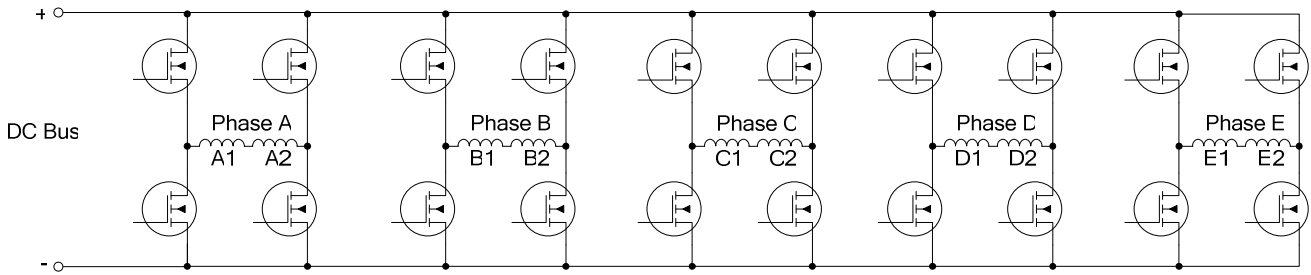


Fig. 3 Bipolar 5 phase H-bridge converter topology

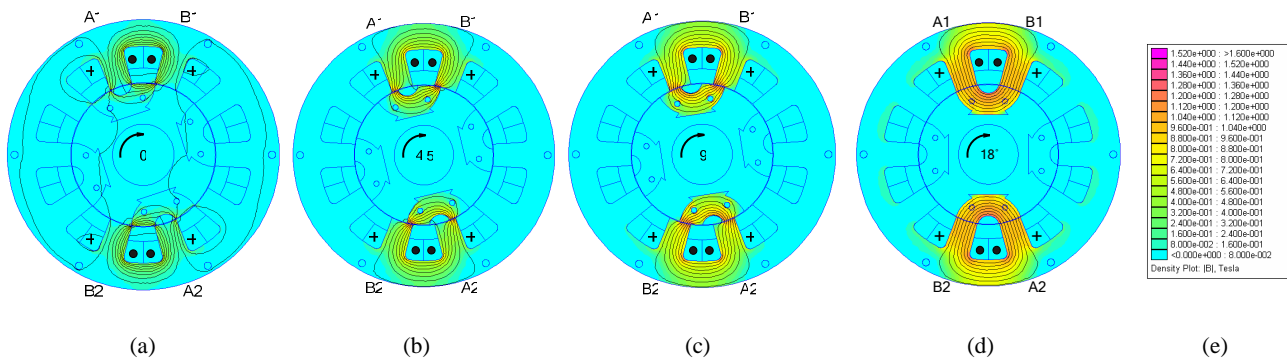


Fig. 4 Operation procedure and flux distributions derived by FEM (a) Excitation starting of A and B phases (unaligned position) (b) A rotation of 4.5° in clock-wise (c) A rotation of 9° in clock-wise (semi-aligned) (d) Totally aligned position (excitation of other two phases already started)

B. Finite Element Based Simulation Results

The torque and inductance plots of ST-SRM under various excitation conditions ($I=3, 5, 7, 10$ and 12 A) as obtained from FEM based simulations are shown in Fig. 5 and Fig. 6.

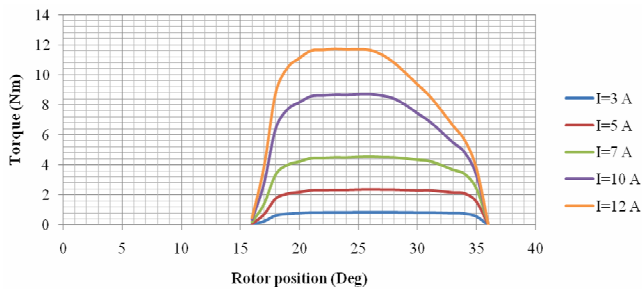


Fig. 5 Torque plots of ST-SRM

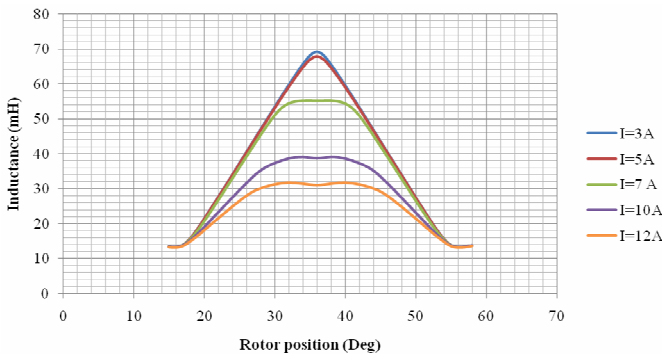


Fig. 6 Inductance profiles of ST-SRM

In Fig. 5 and Fig. 6, only the produced torque and inductance profile in case that the phases A and E are excited are taken into account. At 5 A which is rated current, the developed torque is about 2.34 Nm. The inductance profiles are obtained by developed magnetic field energy using the following equation [5]:

$$E = \frac{1}{2} \cdot L \cdot I^2 \quad (1)$$

Where E is the stored energy in magnetic field, L is the inductance and I is the current.

In Fig. 7, the torque plots over a rotation of 90° are shown. As seen in the plots novel ST-SRM produces smooth torque profiles which has acceptable torque ripple.

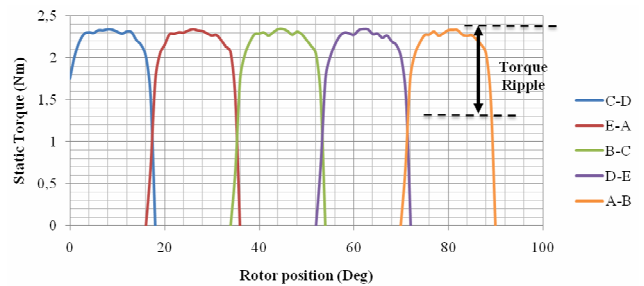


Fig. 7 Torque plots of ST-SRM, $I=5$ A

In Fig. 8, the current-output power characteristic of novel ST-SRM for a given constant speed is shown. Herein, speed is

kept at 105 rad/sn and by changing the excitation current, output power profile is obtained. The plot result given below is smooth enough. And in Fig. 9, for a given current profile, the aligned and unaligned inductances derived via magnetic field energy were calculated and the relation between L_a-L_u (the difference between aligned and unaligned inductances) and output power is given. The performance profile is nearly linear between 5 A and 11 A.

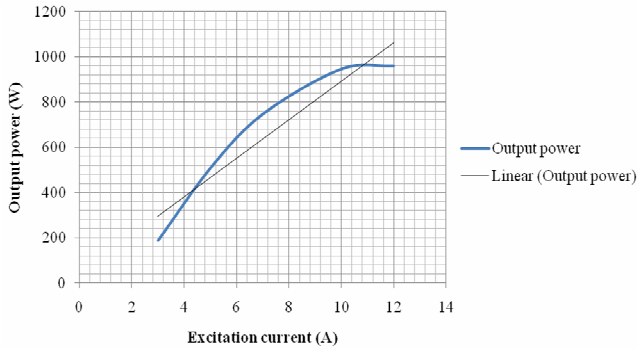


Fig. 8 Current-Output characteristic of ST-SRM, $\omega=105$ rad/sn

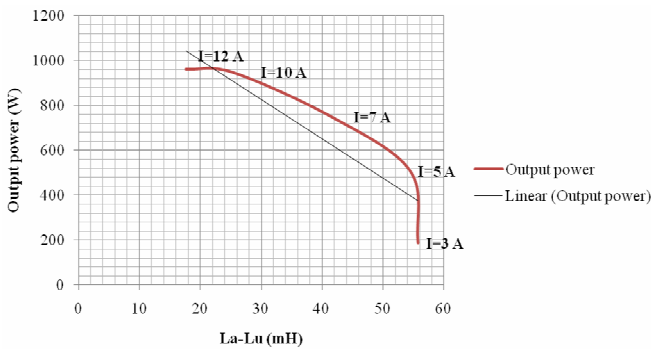


Fig. 9 Inductance-Output characteristic of ST-SRM, $\omega=105$ rad/sn

C. Comparison of Conventional SRM and ST-SRM Simulation Results

The simplified current profiles of ST-SRM and conventional SRM obtained from FEM based simulation study are shown in Fig. 10 and Fig. 11. Since the driver is bipolar, the current plots overlap sometimes.

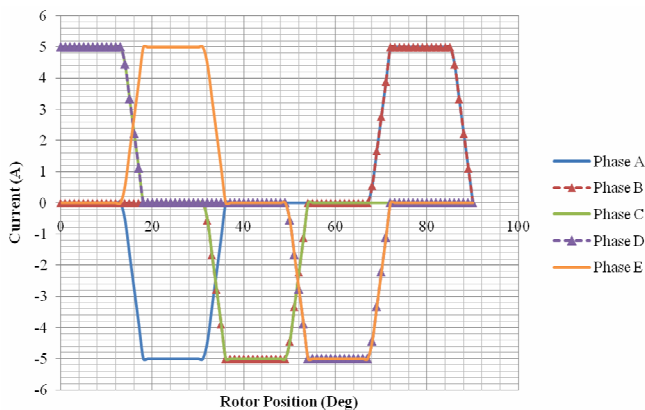


Fig. 10 Simplified current profiles of ST-SRM

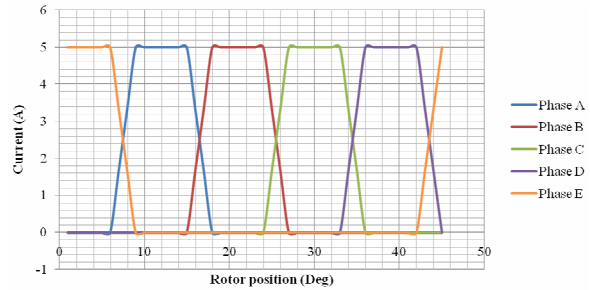


Fig. 11 Simplified current profiles of Conventional SRM

The inductance plots of ST-SRM and conventional SRM are shown in Fig. 12. For the same electrical loading there is a ratio between minimum reluctance of switched reluctance machines[6]. If it is considered that there is a inverse ratio between reluctance and inductance of a path, an equation can be written as follows;

$$\frac{L_{ST-SRM}}{L_{CONV-SRM}} = \frac{T_{ST-SRM}}{T_{CONV-SRM}} \quad (2)$$

Where L_{ST-SRM} is the maximum inductance of ST-SRM, $L_{CONV-SRM}$ is the maximum inductance of conventional 5-phase SRM, T_{ST-SRM} is the maximum torque produced in novel ST-SRM and $T_{CONV-SRM}$ is the maximum torque produced in conventional 5-phase SRM for a given current profile, herein rated current is about 5 A. The result derived from analytical result is about 2.08 while the simulation gives a result of 2.03, so the results are well-agreed.

Eventually, the novel ST-SRM gives a torque output 2 times more than conventional SRM since two phases are excited at all times. The torque profile of the motors are shown in Fig. 13.

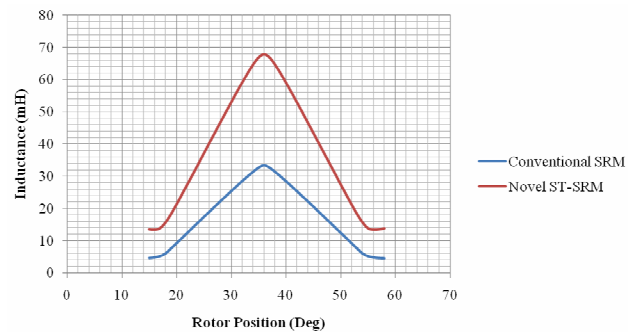


Fig. 12 Inductance plots of ST-SRM and conventional SRM

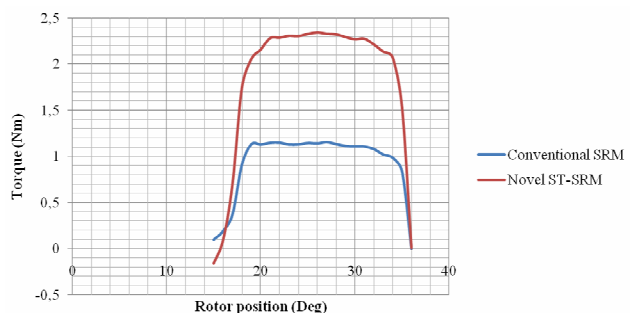


Fig. 13 Torque plots of ST-SRM and conventional SRM

As seen in Table II, it is clear that ST-SRM has the highest operation values as compared to conventional SRM. Especially, torque/weight ratio of the novel ST-SRM is much higher. That proves the performance of the novel ST-SRM.

TABLE II
COMPARISON VARIABLES

Parameter	Novel ST-SRM	Conventional SRM
Maximum torque at 5 A (Nm)	2.34	1.15
Active M530-50A silicon steel weight (kg)	9.90	11.47
Aluminum block weight (kg)	0.71	-
Maximum inductance (mH)	67.91	33.39
Resistance per phase (ohm)	0.56	0.56
Magnetic field energy at 5 A (Joule)	0.848	0.417
Torque/weight ratio (Nm/kg)	0.22	0.1

IV. CONCLUSION

This paper has described design, construction and simulation results of a novel high performance segment type switched reluctance motor with U-type segment rotor cores. It is proved analytically and through finite element based studies that novel ST-SRM gives 2 times more torque than conventional SRM for the same input and design parameters. The simulation results obtained via FEMM 4.2 package are well-agreed with analytical calculations. Especially torque/weight ratio is 2.2 times better than conventional SRM. So as to achieve the best performance, smooth power output and better torque profile; the geometrical parameters of the ST-SRM is optimised.

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