Characteristic Analysis of Two-Phase 4/5-Pole Switched Reluctance Motor

Jin-Woo Ahn*

Abstract – Design and analysis of a novel 2-phase 4/5 Switched Reluctance Motor(SRM) is presented. The proposed motor employs a novel stator pole configuration. A novel SRM employs four-rotor and five-stator poles. The motor has no dead-zone and can be operate at any rotor position. The structure and operating principle are also described. The comparison between the proposed motor and a conventional two-phase 4/2 SRM is undertaken in this analysis. Furthermore, the Finite Element Analysis(FEA) and matlab-simulink are used to predict and simulate the performance of a proposed motor. The results of investigation indicate that the proposed structure offers a better performance in term of torque production.

Keywords: Switched Reluctance Motor, Short magnetic flux, Two-phase, 4/5 pole SRM

1. Introduction

SRM is a double salient and a single excited motor. In general, stator of SRM consists of concentric windings for each pole. The SRM employs no permanent magnet(PM) both in the stator and rotor. The rotor of SRM is basically a piece of steel with laminated shape to form salient poles. Due to its simple structure and robust construction, the SRM has many advantages compared with the other DC of AC machine[1-3]. The advantage of SRM includes low maintenance, fault tolerance and wide speed range in the constant power region. As the result of its advantages and inherent simplicity structure, the SRM promises a reliable and a low-cost variable-speed drive and will undoubtedly take the place of many electrical drives.

In the contrast, two of the main disadvantages are high torque ripple and acoustic noise. As SRM has the doubly salient structure, the torque ripple is caused by torque production which being transferred from one active phase to another. The torque ripple is consequence of the non-linear torque-current-angle characteristics and the discrete nature of torque production mechanism.

The number of stator poles is usually unequal to the number of rotor poles. The difference in the number of poles is to avoid the possibility of the dead-zone where it cannot produce a torque. This condition occurs when all the rotor poles are aligned with the stator poles. In this paper, a novel 2-phase 4/5 SRM is introduced. The motor has four-stator and five-rotor poles. This configuration delivers the magnetic flux flow through the shortest path. In addition, a comparison between conventional 4/2 and 4/5 SRM is undertaken to show its effectiveness. Meanwhile, FEM analysis and matlab-simulink were employed to predict the characteristic and performance of the proposed SRM.

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2. 4/5-Pole Structure

The novel 4/5 SRM is a 2-phase motor with four-stator and five-rotor poles. The difference between proposed motor and conventional 4/2 SRM is that the proposed motor employs a short magnetic flux instead of long diametric magnetic flow as applied in the 4/2 conventional SRM. The advantage of short magnetic flux is able to increase efficiency and torque production while decreasing the losses. But increased the number of rotor pole will increase the switching frequency which is related to the switching loss.

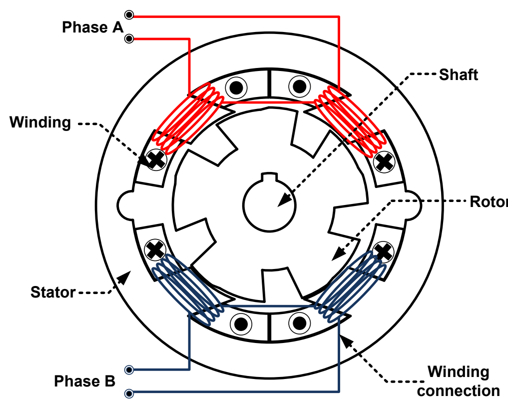


Fig. 1. Cross-sectional view of proposed 4/5SRM

The proposed motor has higher rotor poles instead of conventional 2-phase 4/2 SRM. The five rotor poles in the proposed motor ensures that there is no zero-torque positions and self-starting capability at any rotor position. The symmetric rotor pole is designed to deliver the magnetic flux circulated from one pole to the others. The stator poles of the proposed motor are placed to avoid the dead-zone area. So, the motor can be rotated bidirectional at any rotor position. Fig.1 shows the cross-sectional view of 4/5 pole structure, while Table 1 shows dimension of the proposed SRM, respectively.

Table 1. Dimension of proposed SRM

Parameter	Dimension	Unit
Stator diameter	48	mm
Rotor diameter	27	mm
Bore diameter	27.25	mm
Shaft diameter	8	mm
Motor length	40	mm
Air-gap	0.25	mm
Motor weight	1.2	mm

The windings for each phase are fixed in the slot. In the conventional SRM structure, each coil of the phase windings is wound around a single stator pole. In the proposed motor, each phase comprises two coils wound on neighbor poles and connected in series with consisting numbers of electrically separated circuit or phases. So with the same amount of current excitation, the torque produced in the winding of proposed SRM tends to be higher than that of a single tooth winding in conventional SRM, due to the more effective utilization of both iron and copper materials at any instant. The winding configuration of a proposed motor is shown in Fig. 2.

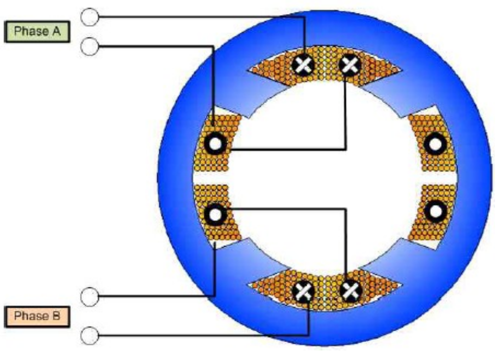
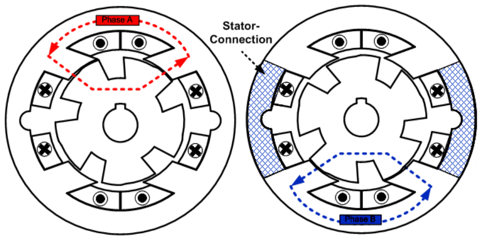


Fig. 2. Winding configuration

The proposed structure is to shorten the flux loops by making each two near stator teeth incorporated with one magnetic circuit, as consequent, the magnetic flux in the one phase will circulate through to the shortest pole path. The magnetic flux path for each phase of 4/5 SRM are shows in Fig. 3.

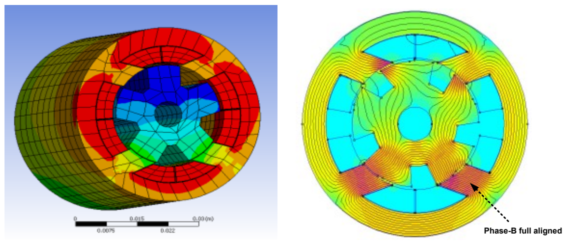


(a)phase A (b) phase B

Fig. 3. Magnetic flux path of 4/5 SRM

3. FEM Analysis

The FEM analysis is undertaken to estimate the performance of the proposed motor. The FEM meshes are shown in Fig. 4. Both 2D and 3D mesh are used to predict the performance of the proposed motor with neglecting the end-winding effect.



(a) 3-D model (b) 2-D model

Fig. 4. Mesh for FEM analysis of 4/5 SRM

In SRM, poles on both rotor and stator are the most important parts of a motor configuration to produces a torque. The proportion of tooth width and air-gap strongly affect to both static and dynamics torque characteristics. In the proposed SRM, the stator poles are designed such a way to drains the magnetic flux through the shortest path. The stator poles are placed symmetrically between phase A and B. The value of maximum flux density used in the proposed motor is maintained 1.7 Tesla for aligned position. The magnetic flux distribution when aligned and unaligned position are shown in Fig. 5.

The magnetic flux distribution when unaligned and aligned of rotor position are not balanced in term of flux distribution in the stator yoke(see Fig.5). Most of flux flows through the shortest path, but a small amount of flux appears through a diametrical stator yoke. This unbalanced flux will produces the unbalance radial force in the stator. In many applications, the unbalanced radial forces, which are result in unequal stator pole arcs in a phase, can be handled by a mechanical compensation.

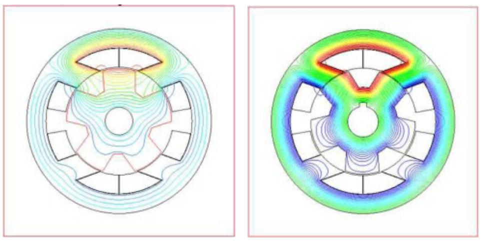


Fig. 5. Flux distribution when unaligned and aligned position

4. FEM Analysis

Characteristic or performance of the motor can be improved by means of optimal excitations as well as magnetic design [5]..

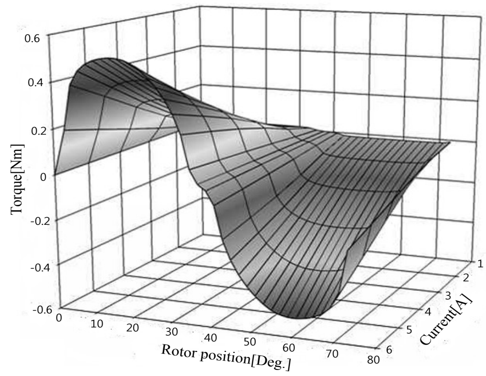


Fig. 6 Torque characteristic

The optimal excitations can be achieved by the shortest path of magnetic flux flow. In a coventional structure, short magnetic flux can be achieved by a proper winding connection. But in the proposed motor, only configuration of winding is not enough to make a magnetic flux through the shortest path. The stator pole shape adjustment is needed to make the magnetic flux flow through the shortest path and eliminate the dead-zone area. The shortest magnetic flux flows require two adjacent phases to be energized at the same times to create the short flux loops and provide a controlled excitation.

The operational principle of a proposed motor is based on the difference in magnetic reluctance for magnetic field lines between aligned and unaligned rotor position. When a stator coil is excited, the rotor experiences a force, pulling the rotor to the aligned position. A positive torque is produced if current flows in a phase winding with inductance of that phase winding are increasing. The rotor will shift to a position where reluctance is to be minimized and thus the inductance of the excited winding is maximized. The relation between torque and exciting current is shown in Fig. 6. While, Fig. 7 shows resultant torque of the proposed type which produced by the continuous switching form phase A to B without optimal control and overlap angle between them.

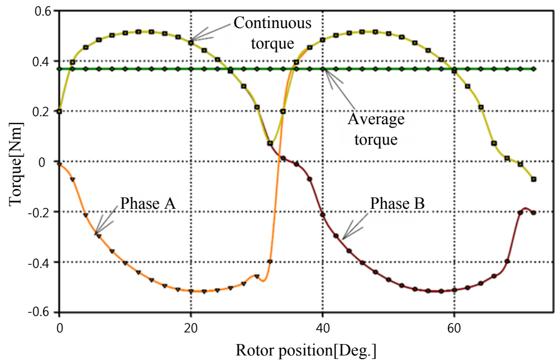


Fig. 7. Resultant torque

At the neutral commutation angle of 36 degree, the motor can produce 17.5% of maximum torque. It means the proposed SRM has no dead-zone even in minimum torque region. The torque performance is shown in Table 2. In the actual control method, the overlap angle is a mandatory. The overlap angle between phases can reduced the torque ripple and increase the overall average torque.

Table 2. Torque performance of 4/5 SRM

Parameter	Dimension	Unit
Max. torque	0.52	Nm
Min. torque	0.07	Nm
Avr. Torque	0.37	Nm
Torque ripple	85.97	%

The other important parameter of the motor is inductance profile. The inductance is proportional to the overlapping area of a rotor and a stator.

The ratio between unaligned and aligned inductance is an important parameter to define the performance of motor briefly. The aligned position is when stator and rotor poles are fully aligned with each other, attaining the minimum reluctance position and phase inductance is maximum at this position. The inductance profile of the proposed motor is shown in Fig 8.

The unsaturated aligned and unaligned incremental motor inductances are the two key reference positions for the controller. A positive torque is produced if current flows in a phase winding as inductance of that phase winding are increasing.

A positive voltage applied to a phase winding in the unaligned rotor position, where the inductance is lowest, and thus, the rise rate of exited current is high. In this region, shear forces are generated, which tend to align the rotor poles. Therefore, the inductance profile as shown in Fig. 8 results in a saturated form.

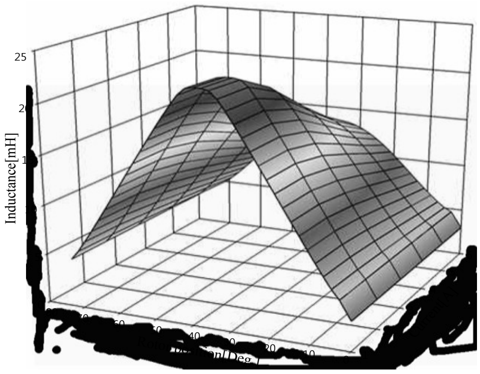


Fig. 8. Inductance profiles

The inductance can be expressed as relation between number of turns and self reluctance of the motor as shown in (1).

$$L = \frac{N^2}{\Re} \quad (1)$$

where, N is the number of turns per phase and $\Re$ is the motor reluctance. The motor reluctance can be determined through the equivalent circuit of a motor. Total reluctance is a sum of reluctances traversed by magnetic flux in one phase.

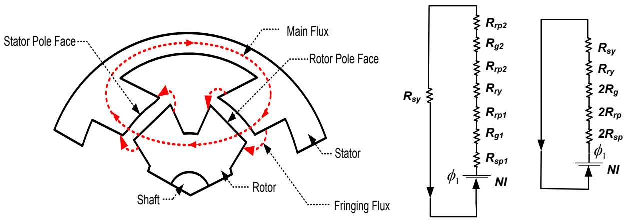


Fig. 9 Equivalent circuit of the proposed motor

The total reluctance between rotor and stator system covers the reluctance of stator yoke (R_{sy}), stator pole (R_{sp}), air-gap (R_g), rotor pole (R_{rp}) and rotor back iron (R_{ry}). Some assumption are takes into account in the calculation. One is ignoring the fringing-flux because the fringing is not very significant and, second is the magnetic flux flows through only one direction. The total reluctance of the proposed motor is shown in Fig. 9.

The total stator-rotor reluctance of the proposed motor is :

$$R_y + R_{ry} + 2R_g + 2R_{rp} + 2R_{sp} \quad (2)$$

In the same fashion with the 4/5 SRM equivalent circuit, the equivalent circuit of a 4/2 SRM is build by separated reluctance as shown is Fig. 10.

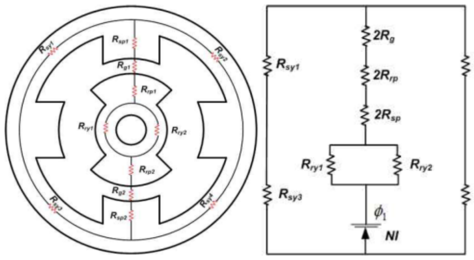


Fig. 10 Equivalent circuit of 4/2 SRM

For the sake of simplicity, it is assumed that the value among (R_{sy}) is same, and the value of (R_{sy1}) is equal to (R_{sy2}). The total reluctance of a 4/2 SRM is :

$$R = R_{sy} + \frac{R_{ry}}{2} + 2R_g + 2R_{rp} + 2R_{sp} \quad (3)$$

The total reluctance of a proposed motor is higher than the conventional motor. In the conventional motor, the flux in both rotor and stator will flow through two directional side of motor yokes. This effect will bring the two reluctances of stator and rotor yoke connected as parallel. However reluctance value of each rotor and stator yoke in conventional motor is higher. This is because that the flux in conventional motor will flow longer than the proposed motor.

Due to salient structure of SRM, the flux exists among the adjacent stator poles and small portion of the flux lines may travel through the air from another close path via another stator-rotor pole pair. This characteristic will effect of inductance changes non-linear with rotor positions.

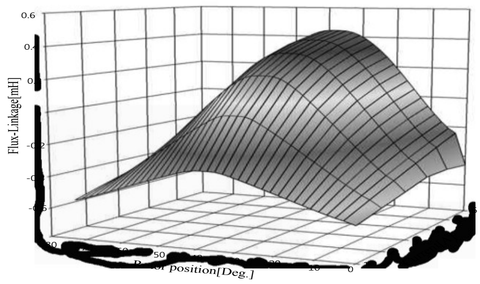


Fig. 11. Flux-current characteristics

The 4/5 SRM has five rotor poles, a rotation of 72 degree from alignment to unalignment of rotor position is sufficient to obtain the flux characteristics of one electrical cycle. The flux characteristic of 4/5 SRM is shown in Fig. 11.

In order to estimate the characteristics of the proposed SRM, a simple matlab-simulink model is made. The model has four blocks. They are asymmetric converter block with contains of two look-up tables data, gate driver block, and rotor position sensor block. From this simulation, the output performance such as torque, excitation current and motor efficiency can be predicted. The simulation result indicates that the proposed motor can produce 0.53 Nm output torque. This result is not differ with the result from the FEM. The matlab-simulink simulation result is shown in Fig. 12.

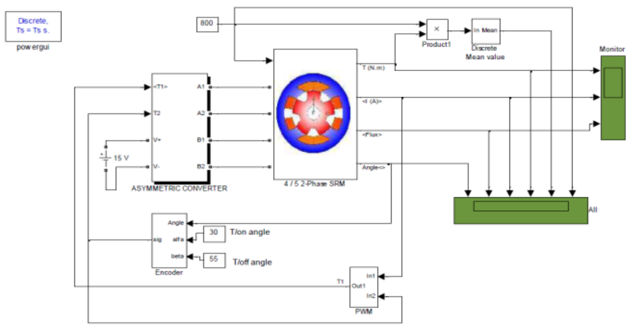
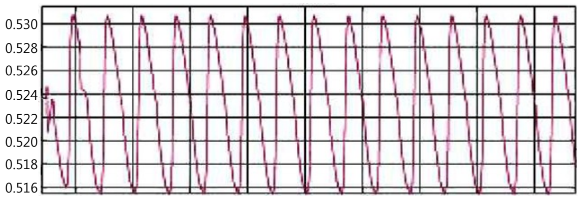
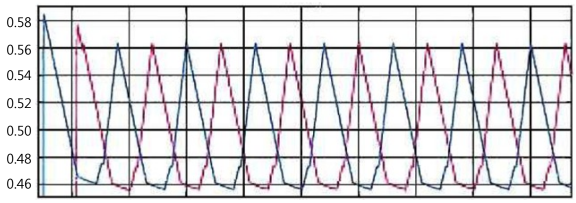


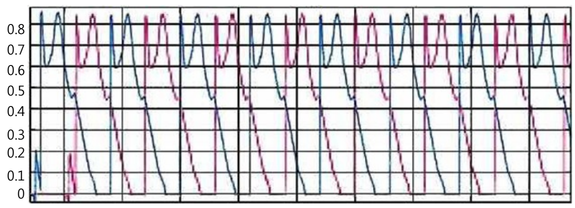
Fig. 12 Matlab-simulink model



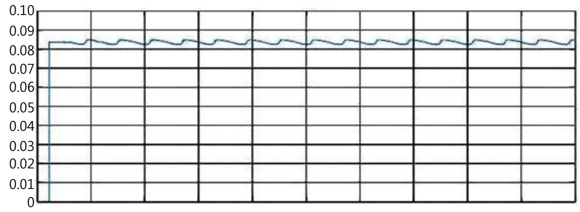
(a) torque



(b) flux



(c) Current



(c) output power

Fig. 13. Simulation results of 4/5 SRM

5. Characteristics Comparisons

The comparison between a novel 4/5 2-phase SRM and conventional 4/2 SRM is executed. The simulation is to compares the performance of a proposed motor. Both 4/2 and 4/5 SRMs are 2-phase machine. The comparisons are dimensions. The 4/2 SRM structure is shown in Fig. 14, while parameters and motor dimensions are shown in Table 2.

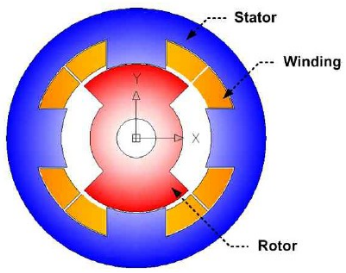


Fig. 14. Structure of 4/2-pole 2-phase SRM

Number of rotor poles is related to the switching frequency of SR drive. When the rotor pole number is high, switching frequency is high but torque interval is small, resulting in lower torque ripple, and also lowering the average torque. The large torque interval brings an advantage of wide positive torque region. The five rotor poles makes a short flux path and requires a reduced MMF. Hence, with the same excitation current, the motor with short magnetic flux can produce higher MMF and generate higher output torque, instead of long magnetic path motor. The comparison of a long magnetic flux motor (4/2 SRM) and a short magnetic flux motor (4/5 SRM) is shown in Fig. 15 while Fig. 16 is shown the efficiency curve of the 4/5 proposed SRM.

Table 3. Parameters utilized in the comparison

Parameter	4/2	4/5	Unit
Stator outer diameter	48	48	mm
Stator inner diameter	27.72	27.72	mm
Stator back iron diameter	38	38	mm
Shaft diameter	8	8	mm
Stack length	40	40	mm
Max. current	6	6	mm

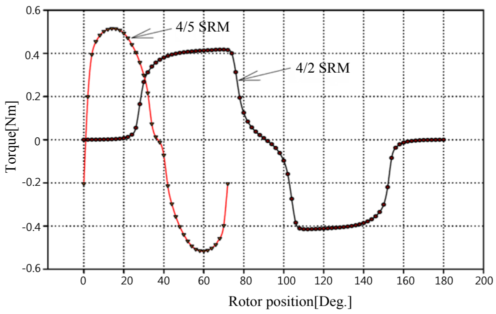


Fig. 15. Torque comparison

A rotor position of 0 degree is the unaligned position, and that are 90 degrees and 36 degrees for 4/2 and 4/5 SRM to aligned with the stator pole. The output peak torque are 0.43 Nm for 4/2 SRM and 0.52 Nm for 4/5 SRM with phase current of 6 Amps.

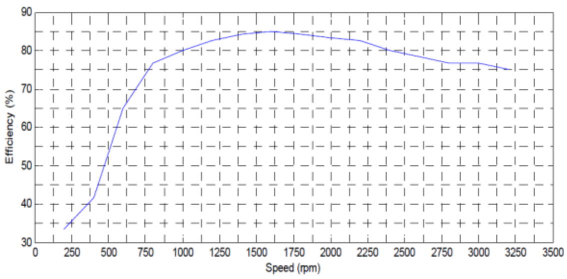


Fig. 16. 4/5 efficiency curve

From this comparison indicated that the proposed novel 4/5 2-phase SRM offers a better performance in term of torque production. The maximum torque produces by the 4/5 SRM is 20% higher than the 4/2 SRM. Moremver, a starting torque produced by the proposed motor is higher than conventional 4/2 SRM. The efficiency in the simulation of the proposed 4/5 SRM is up to 85% at 1625 rpm, which is acceptable for this size of motor.

5. Conclusion

A novel 4/5 2-phase SRM was proposed in this paper. The motor utilizes a new selectrion of stator-rotor poles, determination of main motor dimensions and geometrical optimizations. The stator poles are placed to deliver short magnetic path with no dead-zone at any rotor position. The FEM simulation, matlab-simulink model and comparisons between proposed SRM and conventional 2-phase 4/2 SRM is undertaken to verified the proposed model. The 4/5 proposed SRM offers a better performances in term of torque production.

Acknowledgements

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