Novel Switched Reluctance Motor with Segment Core Embedded in Aluminum Rotor Block

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Though Switched Reluctance Motor (SRM) has been expanding its application area, problems such as low torque/volume ratio, high level vibration and acoustic noise still remain.

Segment type SRM (conventional segment type SRM) had better performance than conventional SRM, because it had twice magnetized poles compared with a usual VR type SRM. Where, the segment cores were arranged on the circumference of the rotor, for example, the segment cores were assembled onto a non-magnetic shaft and held by a stainless steel wedging system and it was potted using an epoxy compound. Therefore, it had some problems of complexity for manufacturing and weakness of mechanical strength.

In this paper, we propose a novel segment type SRM in which the segment core is embedded in aluminum rotor block in order to increase the mechanical strength and easy manufacturing as well as to improve the torque performance. Figure 1 shows the construction of our novel segment type SRM with 6 stator poles and 4 rotor segment cores. The stator has full pitch windings.

Initial design for a 2 kW, 1,800 rpm novel segment type SRM is carried out. The performances are estimated using the two-dimensional finite element method. The effect of the eddy current in the aluminum rotor block is taken into account.

Figure 2 compares the torque characteristics of the novel segment type SRM, the conventional segment type SRM and the VR type SRM at 1,800 rpm. Since four stator poles are excited, maximum torque of both segment type SRMs is twice as that of the VR type SRM. Their average torques are as follows; the novel segment type SRM 10.34 N-m, the conventional segment type SRM 10.07 N-m, the VR type SRM 7.40 N-m.

Figure 3 shows their radial force per one pole at 1,800 rpm. In the region of about 22 degrees, two stator poles of the VR type SRM are attracted to the rotor with large radial forces with 4,000 N, respectively. When the current is switched to another phase at 30 degrees, the poles released from the large attractive force and causes vibration and acoustic noise. In comparatively, four stator poles of the segment type SRMs are, respectively, attracted with 1,400 N at 24 degrees, about one-third of that of the VR type SRM. Therefore, it is expected that the vibration and acoustic noise are reduced rather than the VR type SRM. Their average radial forces per one pole are as follows; the novel segment type SRM 550 N, the conventional segment type SRM 578 N, the VR type SRM 2,244 N.

The performance is also investigated by experiment.
A novel segment type switched reluctance motor (SRM) is proposed, in which the segment core is embedded in aluminum (conductive metal) rotor block in order to increase the mechanical strength and easy manufacturing as well as to improve the performance characteristics and reduce the vibration and acoustic noise. The effect of design parameters on the average torque is investigated using the finite element method. Comparison with conventional VR type SRMs and segment type SRMs without conductive metal construction rotor show the proposed segment type SRM has advantages in the torque performances and the vibration and noise characteristics. The performance is also investigated by experiment.

Keywords: switched reluctance motor, segment core, FEM analysis

1. Introduction

Switched Reluctance Motor (SRM) is expanding it’s application area, such as oil pressure pump, washing machine, etc, because of it’s simple structure, maintenance free and low cost property. However, following problems still remain; low torque/volume ratio, high level vibration and acoustic noise.(1–4)

It was presented that the segment type SRM had better performance than conventional SRM, because it had twice magnetized poles compared with an usual VR type SRM(5) (6). Where, the segment cores were arranged on the circumference of the rotor isolated magnetically, for examples, the segment cores were assembled onto a non-magnetic shaft and held by a stainless steel wedging system and it was potted using an epoxy compound. Therefore, it had some problems of complexity for manufacturing and weakness of mechanical strength. Here, we call such segment type SRM as a “conventional segment type SRM”.

In this paper, we propose a novel segment type SRM in which the segment core is embedded in aluminum (conductive metal) rotor block in order to increase the mechanical strength and easy manufacturing as well as to improve the torque performance. The design parameters are roughly optimized for average torque using the finite element method (FEM) and performance of the final design is compared with the VR type SRM and the conventional segment type SRM(7). Furthermore we show a test machine and measured values of the basic performance(8) (9).

2. Novel Segment Type Switched Reluctance Motor

Figure 1 shows the construction of our novel segment type SRM with 6 stator poles and 4 rotor segment cores. The segment cores are embedded in aluminum rotor block and the stator has full pitch windings. Figure 2 facilitates the understanding of the motor operation. When the A and A phase windings are excited, both side stator poles of the A and A windings are magnetized and the rotor rotates counterclockwise by 30 degree. Then rotor rotates continuously with switching the excitation to B and B, and then C and C.

Though the additional copper loss in the long coil end affects motor efficiency, it is expected that the torque increases because of the twice magnetized stator poles in comparison with the VR type SRM. The eddy current loss in the aluminum rotor block also affects motor efficiency. But, in comparison with the conventional segment type SRM, the flux distributes comparatively in parallel with the circumference of the rotor owing to the eddy current induced in the aluminum rotor block, therefore, the torque characteristics are
3. Initial Design of A Novel Segment Type SRM

3.1 Analytical Model

Initial design for a 2kW, 1,800rpm novel segment type SRM is carried out. Following design parameters are given as shown in Fig. 3; the motor length, or stack height, is 200 mm, the outer diameter of the stator is 160 mm, the outer diameter of the rotor is 89.4 mm, the air gap is 0.3 mm. The torque characteristics are calculated using the two dimensional FEM and the design parameters are roughly optimized for increasing the average torque. Supplied current is assumed as square wave of 8.85 A. The effect of the eddy current in the aluminum rotor block is not taken into account in this chapter.

The finite element mesh is shown in Fig. 4. The number of elements are 24,361 and the number of nodes are 24,924. The air gap region is divided by 3 layers. The number of turns of the full pitch windings is 150.

3.2 Effect of Rotor Segment Depth on Torque Characteristics

Figure 5 shows the torque-angle characteristics for varying the rotor segment depth \( d \), when segment core arc \( \delta_a = 60 \) degrees and aluminum region arc \( \delta_b = 30 \) degrees. The stator pole arc is kept constant at \( \delta_c = 43 \) degrees.

The maximum torque increases with increasing \( d \), but the value saturates from about \( d = 14 \) mm. In this case, the torques decrease in the region between 20 degrees and 30 degrees, because the flux leaks between the bottom of the active and non-active segment cores. The highest average torque is obtained when \( d = 14 \) mm.

3.3 Effect of Rotor Segment Core Arc on Torque Characteristics

Figure 6 shows the effect of varying the rotor segment core arc \( \delta_a \) on the torque characteristics. The
sum of $\delta_a$ and $\delta_b$ is 90 degrees. The rotor segment depth $d$ is 14 mm and $\delta_c = 43$ degrees.

It is shown that the motor with larger $\delta_a$ has larger starting torque at 0 degree and after getting the maximum value it decreases to zero at 30 degrees. The average torque becomes maximum when $\delta_a = 68$ degrees. After investigation for another combinations of $d$ and $\delta_a$ we decide $d = 14$ mm and $\delta_a = 68$ degrees are satisfactory combination.

3.4 Effect of Stator Pole Arc on Torque Characteristics

Figure 7 shows the effect of varying the stator pole arc $\delta_c$ on the torque characteristics. Where, $d = 14$ mm and $\delta_a = 68$ degrees. With increasing $\delta_c$, the torque at 0 degree increases but the average torque decreases. The maximum value of the average torque is gained at $\delta_c = 35$ degrees.

4. Comparison of Performance Characteristics of Three Type SRMs

4.1 Analytical Model

Figure 8(a) shows the FEM mesh of the final 2 kW, 1,800 rpm segment type SRM model. The number of elements are 28,832 and the number of nodes are 29,240. The motor length is 200 mm. The outer diameter of the stator is 160 mm, the outer diameter of the rotor is 89.4 mm, the air gap is 0.3 mm, the stator pole arc is 35 degrees, stator back iron thickness is 10 mm, the rotor segment core arc is 68 degree, and depth of the segment is 14 mm.

The effect of the eddy current in the aluminum rotor block is taken into account in this chapter. The calculation is carried out using the 2-dimensional FEM analysis but the conductivity of the aluminum is corrected by the Russell-Norsworthy coefficient $^{10}$ as a quasi-3-dimensional analysis. The correction factor is 0.98 that means affect of the current spanning in the circumferential direction is very small. Because, the length of the current path in the axis direction of the rotor is 200 mm while the pole pitch of the current path is about 8 mm.

Figure 8(b) shows the comparative VR type SRM whose dimensions, for examples outer diameter of the stator, outer diameter of the rotor, air gap, stator pole arc, are same as the segment type one. The number of elements is 31,435 and the number of nodes is 31,876.

4.2 Torque Characteristics

Figure 9 shows the torque versus angle characteristics at 1,800 rpm. A solid line shows the torque of the novel segment type SRM with aluminum rotor block, a dotted line shows the conventional segment type SRM without aluminum rotor block, and an alternate long and short dash line shows the VR type SRM. The typical drive current, shown in Fig. 10, is given to the three type SRMs.
Since four stator poles are excited, maximum torque of both segment type SRMs is twice as that of the VR type SRM, two poles are excited.

The novel segment type SRM has a little different torque characteristic from the conventional segment type SRM. Because, the flux and eddy-current of the novel segment type SRM with aluminum rotor block produce additional positive or negative torques according to their respective direction of each angle.

Their average torques are as follows; the novel segment type SRM 10.34 N-m, the conventional segment type SRM 10.07 N-m, the VR type SRM 7.40 N-m. The effect of the aluminum rotor block on the average torque is not so great in this case. The effect will be increased by further optimized design and use of time varying drive current.

4.3 Radial Force Characteristics Figure 11 shows the radial force versus angle characteristics per one pole at 1,800 rpm. The solid line shows the radial force of the novel segment type SRM, dotted line shows the conventional segment type SRM, and alternate long and short dash line shows the VR type SRM. They are driven by the typical drive current, shown in Fig. 10.

In the region of about 22 degrees, two stator poles of the VR type SRM are attracted to the rotor with large radial forces with 4,000 N, respectively. When the current is switched to another phase at 30 degrees, the poles released from the large attractive force and causes vibration and acoustic noise. In comparatively, four stator poles of the...
segment type SRMs are, respectively, attracted with 1,400 N at 24 degrees, about one-third of that of the VR type SRM. Therefore, it is expected that the vibration and acoustic noise are reduced rather than the VR type SRM.

Their average radial forces per pole are as follows; the novel segment type SRM 550 N, the conventional segment type SRM 578 N, the VR type SRM 2,244 N.

4.4 Flux Distributions Figure 12 shows the flux distributions of the segment type SRMs and the VR type SRM at 8 degrees. It is confirmed that the segment type SRMs have two small flux loops through two stator poles and one segment core while the VR type SRM has two large flux loops through two stator poles and two rotor poles. It is shown in comparison with the conventional segment type SRM without the aluminum rotor block that the flux of the novel segment type SRM don’t penetrate in the aluminum rotor block and distributes in parallel with the circumference of the rotor owing to the eddy current induced in the aluminum rotor block. The flux distributions at 23 degrees are shown in Fig. 13. Nearby, the radial force has maximum for each SRM.

Figure 14 shows the eddy-current and flux distributions of the novel segment type SRM at 8 and 23 degrees. The eddy-current flows in the aluminum rotor block just nearby active segment core surface (gray region).

5. Experiment

5.1 Test Machine Figure 15 shows the construction of our 2.2 kW 1,800 rpm experimental segment type SRM with 6 stator poles and 4 rotor segment cores. The segment cores are embedded in the aluminum rotor block and the stator has 150 turns full pitch windings. The motor length is 100 mm and the air gap length is 0.3 mm. Figure 16 shows photos of the stator and rotor core. The test machine rotates smoothly and silently.

5.2 Basic Performance The output characteristics of the segment type SRM is compared with the VR type SRM whose design parameters are identical except for the rotor construction and stator windings in which two 75 turns concentrated windings are connected in series. Figure 17 shows the efficiency and power factor versus output power characteristics at 1,800 rpm. In the experiment, the control parameters for the VR type SRM are decided using the optimized approximate equations of the advanced firing angle $\theta_{AF}$ and cut-off angle $\theta_{CF}$ for high efficiency. But the control parameters for the segment type SRM are roughly selected now, $\theta_{AF} = 10$ degrees and $\theta_{CF} = 15$ degrees. The VR type SRM becomes state of pull out at 1,000 W. Though the efficiency of the novel segment type SRM is little smaller than the VR type SRM from 500 to 1,000 W regions, it is constant of about 80% for each output power. The efficiency will be much improved with increasing the number of poles, for examples 12 stator poles and 8 rotor segment cores, because of decreasing the coil end length.

Figure 18 shows the current versus output power characteristics at 1,800 rpm. It is confirmed that the output power
(torque) is greater than that of the VR type SRM by about 40% under the same current condition.

6. Conclusions

Novel segment type SRM with aluminum rotor block is proposed. The performance characteristics are investigated by FEM. The novel segment type SRM increases in the average torque by 40% in comparison with the VR type SRM of same size. Where, the vertical force for one pole reduces by 76%. On this design, the novel segment type SRM increases in the average force by 2.7% and reduces in the vertical force for one pole by 4.8% comparing with the conventional segment type SRM. The difference will widen owing to improvement on the motor design and control.

It is also confirmed from the test results that the output power and torque of the novel segment type SRM are increased by about 40% than the same-sized VR type SRM supplied the same current.

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