A Characteristic Experiment of 4-phase Segment Type Switched Reluctance Motor

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***Abstract*--Authors developed a novel segment type switched reluctance motor (SRM) as a rare earth less motor. The torque was increased by 40% and the radial force was decreased by 76% compared with the same size VR type SRM. Increasing the average torque, however, caused increasing torque ripple. In this paper we propose a 4-phase segment type switched reluctance motor and show that the torque ripple can be decreased by controlling the excitation current.**

***Index Terms*-- Four phase, Segment type, Switched reluctance motor, Torque ripple characteristic**

I. INTRODUCTION

A switched reluctance motor (SRM) is expanding its application area, such as high speed application, home electric appliances, etc, because of its adequate mechanical strength, simple structure, maintenance free and low cost. However, it remains for us to improve performance characteristics and reduce acoustic noise and vibration [1] [2].

We previously proposed a novel segment type SRM in which stator windings were full-pitch winded and segment cores were embedded in an aluminum rotor block [3] [4] in order to increase the mechanical strength and easy manufacturing compared with usual segment type SRM as well as to improve the torque performance and reduce the vibration and acoustic noise compared with conventional VR type SRM.

This paper describes analytical and experimental characteristics of a 4-phase segment type switched reluctance motor deigned to decrease the torque ripple under two phases excitation control.

II. SEGMENT TYPE SRM

A. 3-Phase Segment Type SRM

Fig. 1 shows construction of the 3-phase novel segment type SRM. Segment cores are embedded in the aluminum rotor block and the stator has full pitch three phase windings. Fig. 2 shows torque waveform of the SRM simulated by finite element method (FEM). The maximum torque of the segment type SRM is twice as that of a same-sized variable reluctance (VR) type SRM. The average torque is increased by 40%. The radial force is smaller and so the vibration and acoustic noise are smaller than the VR type SRM, because four poles among the six poles are always excited. The iron loss is low because the magnetic path is short [4]. Fig. 3 shows the power factor and efficiency of a 2.2 kW, 1,800rpm test machine. It is shown that the efficiency is about 77% between 400 W and 1700 W.

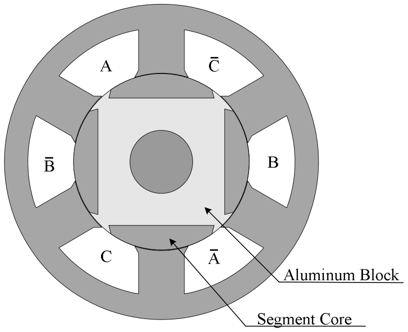


Fig. 1. Construction of 3-phase segment type SRM.

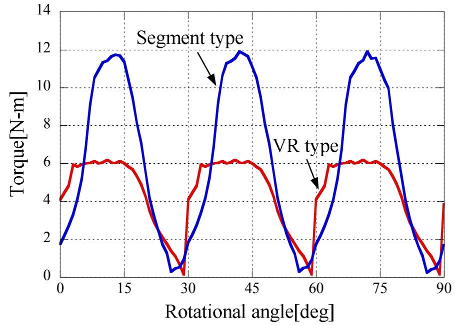


Fig. 2. Torque waveform of 3-phase segment type SRM.

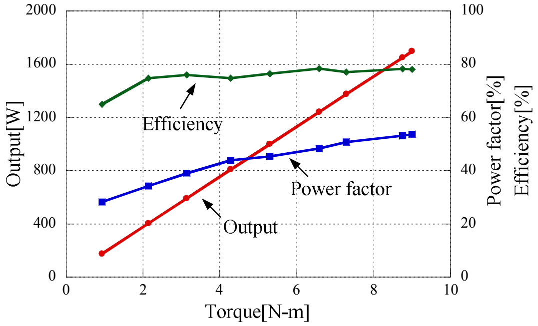


Fig. 3. Characteristics of test machine of 3-phase segment type SRM.

B. 4-Phase Segment Type SRM

Fig. 4 shows construction of a 4-phase segment type SRM. The stator has full pitch 4 phase windings. A diameter of the aluminum rotor block is shorter than a diameter of the rotor in order to decrease eddy current loss in the aluminum rotor block. Fig. 5 shows the analytical torque characteristics in comparison with the 3-phase SRM. The 4-phase SRM is analyzed under tow phases excitation control, in which two phase windings are excited simultaneously. It is shown that the torque ripple of the 4-phase SRM is greatly improved.

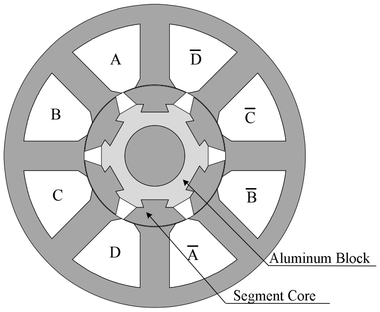


Fig. 4. Configuration of 4-phase segment type SRM.

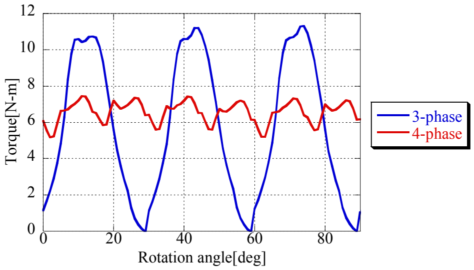


Fig. 5. Torque characteristics (FEM analysis).

III. DRIVE SYSTEM

Fig. 6 shows a experimental drive system. The photo is shown in Fig. 7. It has a control unit, a diode bridge circuit and three inverter units. Here, hard chopping drive is performed. The switching frequency of the inverter is 15 kHz. The drive system enables bipolar control, but this time the experiments are carried out on unipolar control.

IV. EXPERIMENTAL RESULT

A. Input Current Waveform

Fig. 8 (a) shows the experimental current wave form at 600 rpm. The current is supplied to the stator windings during period of time corresponding 15 degree of the rotational angle. In this case, single phase of the stator windings is excited every time. In Fig 8 (b), the current is supplied to the stator windings during period of time corresponding 22.5 degree of the rotational angle. In this case, two phases are excited instantaneously every time.

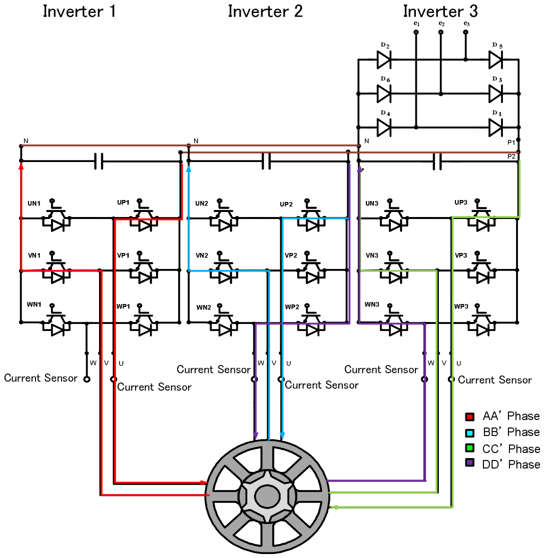
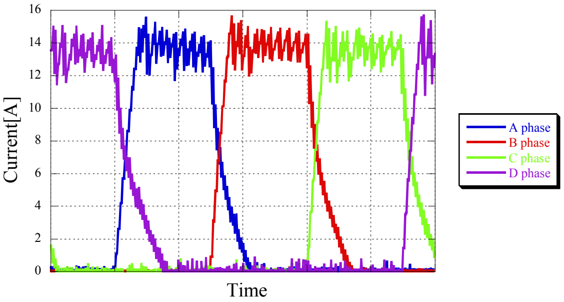


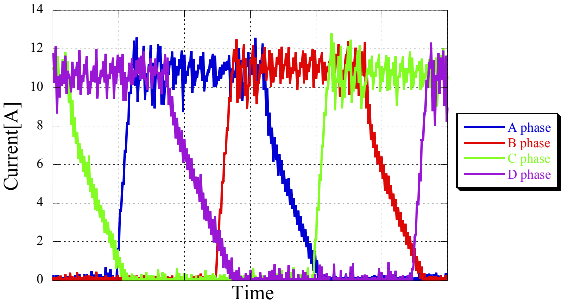
Fig. 6. SRM drive system.

Fig. 9 (a) shows the experimental current wave form at 1800 rpm. When the rotational speed is 600rpm, the current waveform is nearly constant. However, when the rotational speed is 1800rpm, the current wave form becomes not constant caused by increasing of back electromotive force and inductance. The current waveform also becomes such as a saw tooth wave is superimposed.

Fig. 7. Photo of drive system.

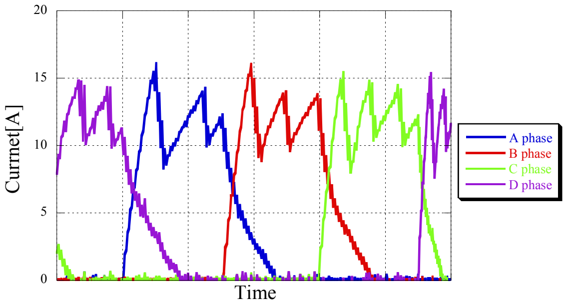


(a) 15deg.

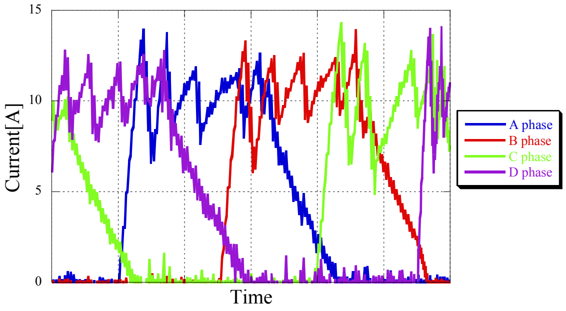


(b) 22.5deg.

Fig. 8. Current waveform at 600 rpm.



(a) 15deg.



(b) 22.5deg.

Fig. 9. Current waveform at 1800 rpm.

B. *Torque Ripple Characteristics*

The experimental system cannot measure instantaneous torque value. Therefore, torque ripple is estimated using FEM analysis, where we use experimental instantaneous current values as the input currents.

Fig. 10 and Fig. 11 show the torque waveform corresponding to the current wave forms shown in Fig. 8 and Fig. 9. The torque wave form of 15 degree of the rotational angle means the torque wave form driven under single phase current control and that of 22.5 degree means under two phases current control. On the torque of 22.5 degree, the maximum value becomes small but the minimum value becomes large comparing with that of 15 degree. Consequently it is shown that the torque ripple under two phases current control is reduced well rather than the single phase current control. The wave form at high speed region has large noise and the torque ripple becomes large.

Torque ripple factor characteristics in each rotational speed are shown in Table I. The torque ripple factor is calculated by the equation (1).

$$\text{Torque ripple factor} = \frac{\text{Max. torque - Min. torque}}{\text{Average torque}} \times 100\% \quad (1)$$

It is shown that the torque ripple is reduced by increasing the excitation width. It means the rotational angle that each stator winding is excited. We can confirm that the torque ripple is reduced by exciting two phase currents of the 4-phase SRM simultaneously.

Table II shows the torque ripple factor characteristics varying the average torque at 600rpm. The excitation width is 22.5deg.

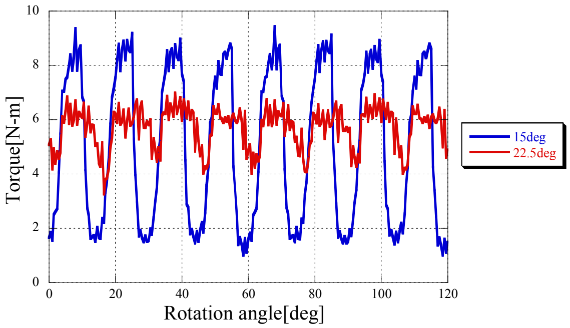


Fig. 10. Torque wave form at 600rpm.

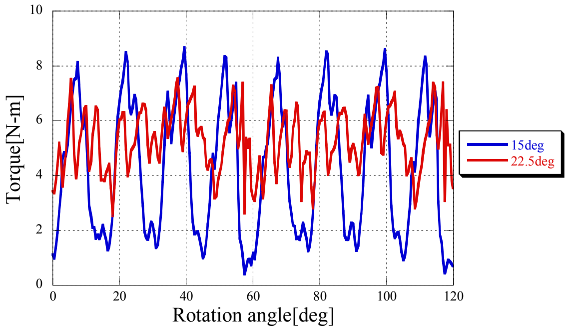


Fig. 11. Torque wave form at1800rpm.

TABLE I
TORQUE RIPPLE FACTOR CHARACTERISTICS

Rotational speed[rpm]	Excitation width[deg]	Torque ripple factor[%]
300	15	169.4
	22.5	52.7
600	15	168.0
	22.5	65.8
1200	15	149.6
	22.5	72.0
1800	15	193.3
	22.5	95.2

TABLE II
TORQUE RIPPLE FACTOR CHARACTERISTICS

Average torque[N-m]	Torque ripple factor[%]
3	52.75
5	54.13
7	56.97

The torque ripple increases slightly with increasing the average torque.

C. *Output Characteristics*

Fig. 12 (a), (b) show the current R.M.S value – output characteristics of excitation width of 15deg and 22.5deg. The rotational speed is 600rpm and 1800rpm, respectively. When the rotational speed is high, the output of 22.5deg excitation width is lower than that of 15 deg at the same current.

D. *Efficiency Characteristics*

Fig. 13 (a), (b) show the current R.M.S value – efficiency characteristics. Though the efficiency of excitation width of 22.5deg is lower at small current region, both excitation width of 15deg and 22.5deg have almost same efficiency characteristics. On the experiment of the 3-phase segment type SRM was a little under 80% of efficiency as shown in Fig. 3. Nearly 80 % efficiency is obtained in the 4-phase segment type SRM. Here, the turn-on angle and the excitation width are not optimized now. In future, the efficiency will be increased under the optimal turn-on angle and the excitation width.

V. CONCLUSIONS

A 4-phase segment type SRM is tested under single phase excitation control as well as two phases excitation control. It is confirmed that the torque ripple is decreased well by driving under two phases excitation control. The maximum efficiency of the 4-phase segment type SRM is nearly 80%.

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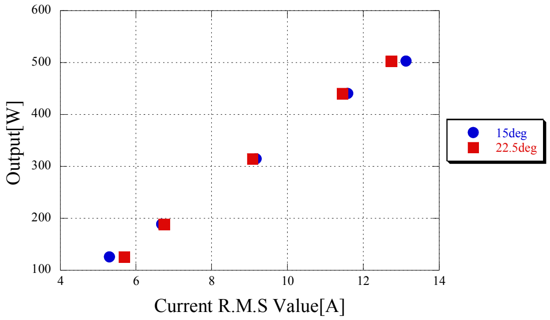
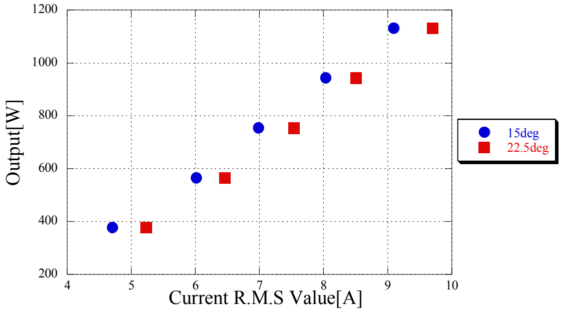
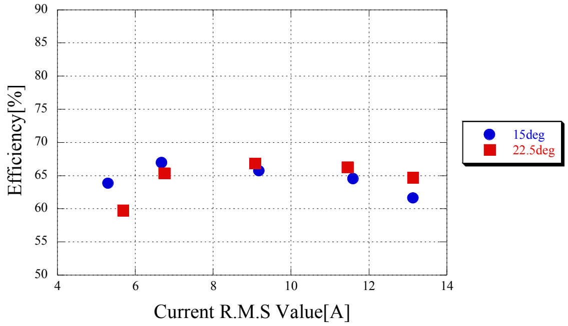


(a) 600 rpm.

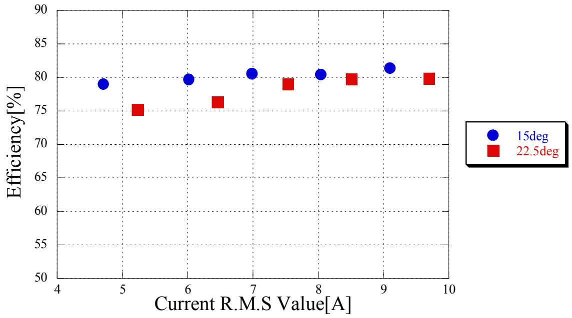


(b) 1800 rpm.

Fig. 12. Output characteristics.



(a) 600 rpm.



(b) 1800rpm.

Fig. 13. Efficiency characteristics.