http://dx.doi.org/10.11142/jicems.2014.3.3.235
Journal of International Conference on Electrical Machines and Systems vol. 3, no. 3, pp. 235~240, 2014

Characteristics of a 4-phase Segment Type Switched Reluctance Motor

Tsuyoshi Higuchi*, Daiki Yamaguchi*, Takashi Abe* and Yuichi Yokoi*

Abstract - A novel segment type switched reluctance motor (SRM) as a rare-earth-less motor is proposed. The torque was increased by 40% and the radial force was decreased by 76% compared with the same size usual variable reluctance (VR) type SRM. Increasing the average torque, however, caused increasing torque ripple. In this paper we develop a 4-phase segment type SRM and show that the torque ripple can be decreased well.

Keywords: Switched reluctance motor, Segment type, Torque ripple reduction

1. Introduction

A switched reluctance motor (SRM) is expanding its application area, such as high speed application, home electric appliances, etc. Because it has special features such as adequate mechanical strength, simple structure, maintenance free and low cost [1] [2]. It is now expected for electric cars as rare-earth-less motors. However, it remains for us to improve performance characteristics and reduce acoustic noise and vibration. It was presented that a segment type SRM had better performance than a conventional variable reluctance (VR) type SRM, because it had twice magnetized poles compared with the VR type SRM [3]. Where, the segment cores were arranged on 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. We previously proposed a novel segment type SRM in which 3-phase stator windings were full-pitch windings and segment cores were embedded in an aluminum rotor block [4] [5]. It was aimed to increase the mechanical strength and easy manufacturing as well as to improve the torque performance and reduce the vibration and acoustic noise compared with the VR type SRM. The motor produced large torque, but the torque ripple was larger than the VR type SRM. To decrease the torque ripple we consider the skewed rotor construction [6]. The torque ripple was reduced by 19%, however the average torque was also reduced by 10% compared with the segment type SRM.

Then we proposed 4 or 5 phases type SRM driven by two phases excitation control to decrease the torque ripple [7]. In this paper, we describe analytical and experimental characteristics of a 4-phase segment type switched reluctance motor. It is shown that the torque ripple is decreased well comparing the 3-phase segment type SRM [8].

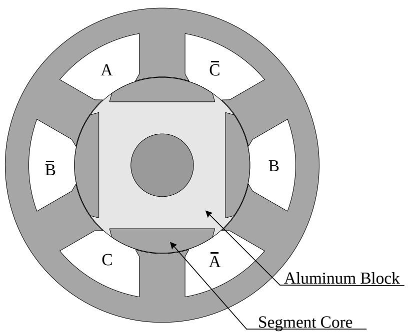


Fig. 1. Construction of 3-phase segment type SRM

2. Segment type SRM

Fig. 1 shows the construction of the proposed 3-phase novel segment type SRM. Segment cores are embedded in the aluminum rotor block and the stator has full pitch 3-phase windings. Fig. 2 shows its torque waveform given by finite element method (FEM) simulation. Fig. 3 compares the flux distribution of the segment type SRM and that of the VR type SRM. The maximum torque of the segment type SRM is twice as that of the same-sized VR type SRM.

The average torque is increased by 40%. The radial force is smaller and so the vibration and acoustic noise are

* Dept. of Electrical and Electronic Engineering, Nagasaki University, Japan (thiguchi@nagasaki-u.ac.jp)
Received 18 April 2013; Accepted 22 July 2014

smaller than the VR type SRM, because four poles among the six poles are always excited. Flux of the segment type SRM distributes around the slot. Since the magnetic path is shorter, consequently, the iron loss is lower than the VR type SRM [4], [5].

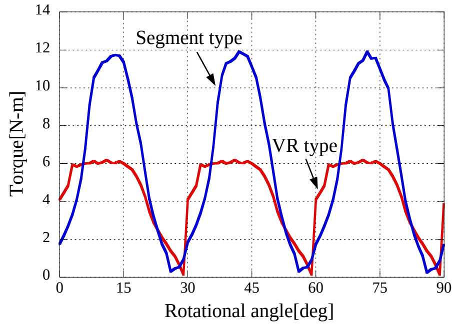
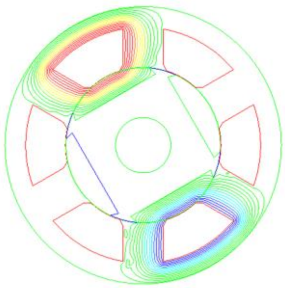
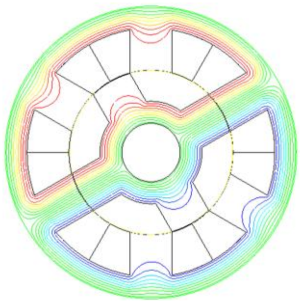


Fig. 2. Torque waveform of 3-phase segment type SRM



(a) Novel segment type SRM



(b) VR type SRM

Fig. 3. Flux distributions of 3-phase SRMs

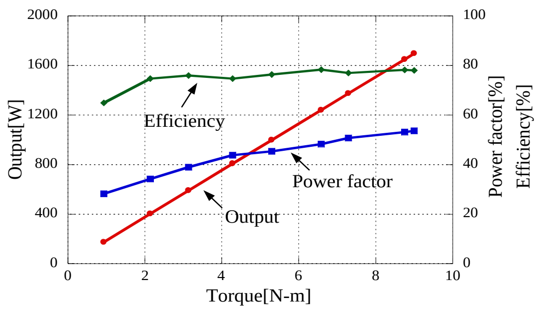


Fig. 4. Experimental characteristics of 3-phase segment type SRM (1800 rpm)

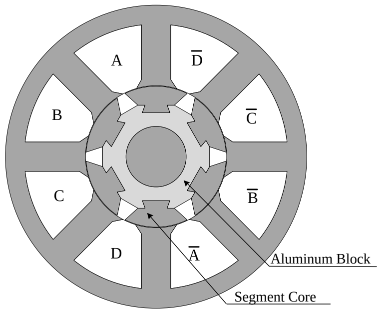


Fig. 5. Configuration of 4-phase segment type SRM

Fig. 4 shows the power factor and efficiency of a 2.2 kW, 1,800 rpm test machine. It is shown that the efficiency is about 77 % etween 400 W and 1700 W [4], [5].

It is found from analytical and experimental research that the segment type SRM has good performance but the torque ripple is very large as shown in Fig. 2.

3. Experimental System of 4-Phase SRM

3.1 Motor construction

A 4-phase segment type SRM is designed for decreasing the torque ripple. Fig. 5 shows construction of it. The motor length, air gap length, outer diameter of the stator and outer diameter of the rotor are 100 mm, 0.3 mm, 160 mm and 74.4 mm, respectively. The stator has full pitch 4 phase windings. An outer diameter of the aluminum rotor block is shorter than the outer diameter of the rotor in order to decrease eddy current loss in the aluminum rotor block. Fig. 6 shows its analytical torque characteristics in comparison with the 3-phase segment type SRM. In simulation of the 4-phase SRM, two phase windings are excited simultaneously. It is shown that the torque ripple of the 4-phase type is greatly improved.

3.2 Drive System

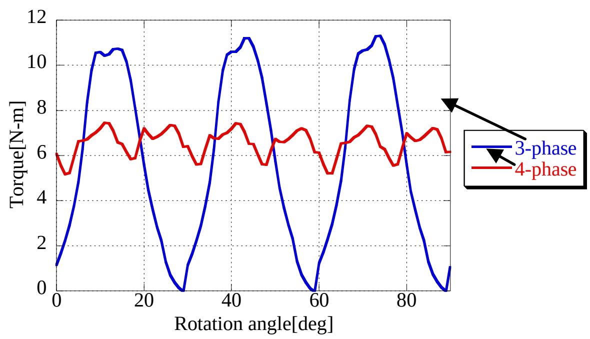


Fig. 6. Torque waveform of 3 and 4-phase segment type SRMs

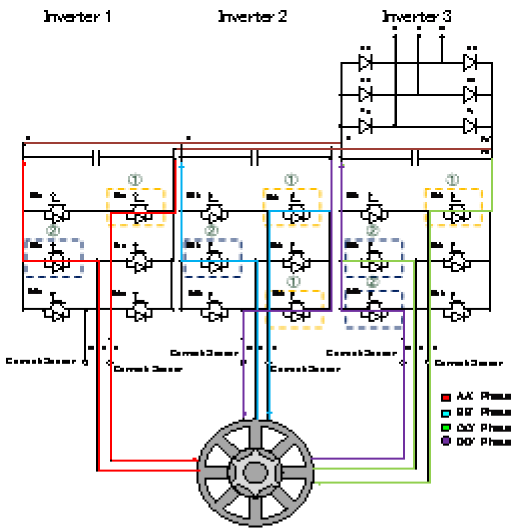
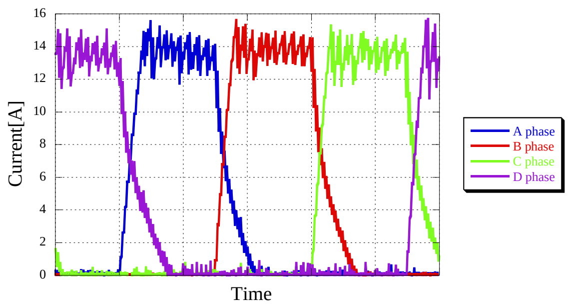
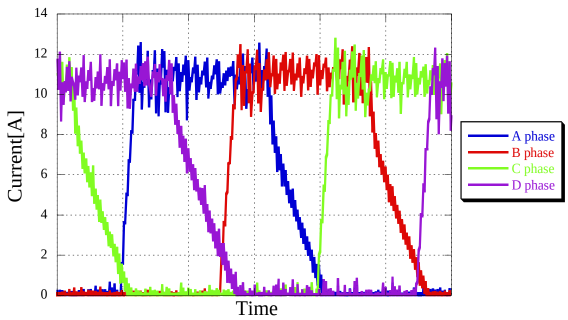


Fig. 7. SRM drive circuit

Fig. 8. Photo of experimental system



(a) 15.0 degree (Single phase control)

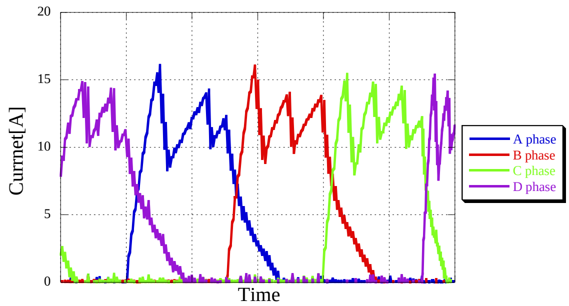


(b) 22.5 degree (Two phases control)

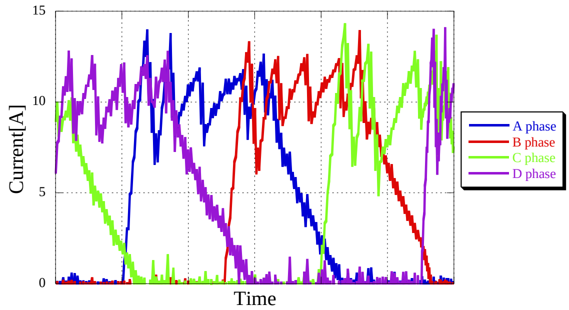
Fig. 9. Current waveform at 600 rpm

Fig. 7 shows the drive circuit. The drive system has a control unit, a diode bridge circuit and three inverter units. The switching frequency of the inverter is 15 kHz. The drive system enables bipolar control, but in this time the experiments are carried out under unipolar control. Fig. 8 is the photo of the experimental system.

4. Experimental Results



(a) 15.0 degree (Single phase control)



(b) 22.5 degree (Two phases control)

Fig. 10. Current waveform at 1800 rpm

4.1 Input current waveform

Fig. 9 (a) shows the experimental current waveform at 600 rpm. The current is supplied to the stator windings during period of time corresponding 15.0 degree of the rotational angle. We call it excitation angle from now. In this case, one phase of the stator windings is excited every time. Fig 9 (b) shows the current waveform when the excitation angle is 22.5 degree. In this case, two phases are excited simultaneously every time.

Figures 10 (a) and (b) show the experimental current waveform at 1800 rpm. When the rotational speed is 1800 rpm, the current waveform does not become constant due to the increase of back electromotive force and inductance. A saw-tooth-wave noise is also detected on the current waveform.

4.2 Torque ripple characteristics

Our experimental system cannot measure instantaneous torque value. Therefore, torque ripple is estimated using FEM analysis, where experimental instantaneous currents are given as current sources.

Table 1. Torque ripple factor

Rotational speed [rpm]	Excitation angle [degree]	Torque ripple factor [%]
300	15.0	169.4
	22.5	52.7
600	15.0	168.0
	22.5	65.8
1200	15.0	149.6
	22.5	72.0
1800	15.0	193.3
	22.5	95.2

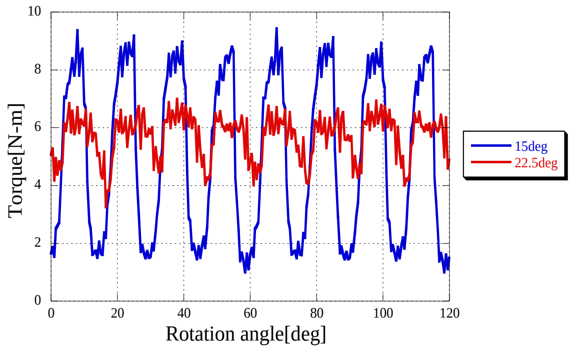


Fig. 11. Torque waveform at 600 rpm

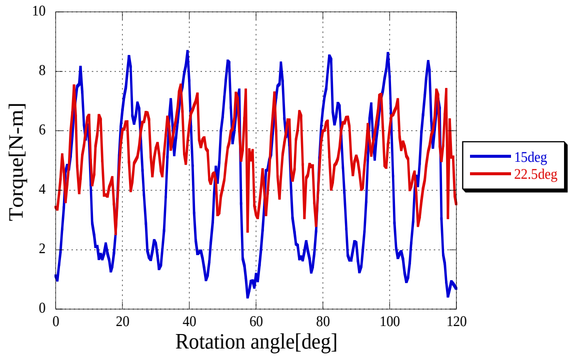


Fig. 12. Torque waveform at 1800 rpm

Figs. 11 and 12 show the torque waveforms corresponding to the current waveforms shown in Figs. 9 and 10. The motor is driven under single phase control at the excitation angle of 15.0 degree and under two phases control at 22.5 degree.

On the torque of 22.5 degree, the maximum torque becomes smaller and the minimum torque becomes larger than that of 15.0 degree. Consequently it is shown that the torque ripple under two phases control is reduced well rather than the single phase control. The large torque ripple at high speed region (Fig. 12) results from the current ripple shown in Fig. 10. Torque ripple factor is shown in Table 1. The torque ripple factor is calculated by (1).

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

It is confirmed that the torque ripple factor is reduced well by increasing the excitation angle, that is by exciting two phases simultaneously.

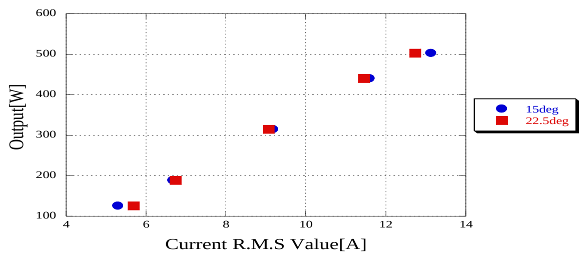
Table 2 shows the torque ripple factor for the average torque at 600 rpm. The excitation angle is 22.5 degree. The torque ripple factor increases slightly with increasing the average torque.

Table 2. Torque ripple factor

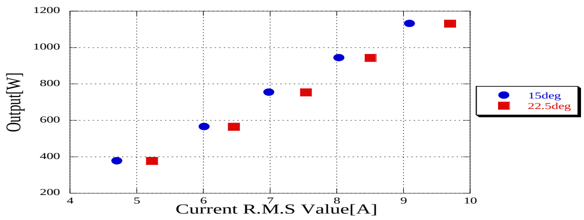
Average torque [N-m]	Torque ripple factor [%]
3.0	52.75
5.0	54.13
7.0	56.97

4.3 Output characteristics

Figs. 13 (a) and (b) show the root mean square (RMS) current–output characteristics when the excitation angle is set at 15.0 degree and 22.5 degree. The rotational speed is fixed at 600 rpm and 1800 rpm. When the rotational speed is high, the output of 22.5 degree is smaller than that of 15.0 degree at the same current.



(a) 600 rpm



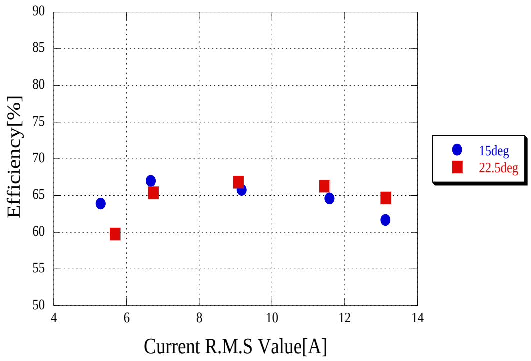
(b) 1800 rpm.

Fig. 13. Output characteristics

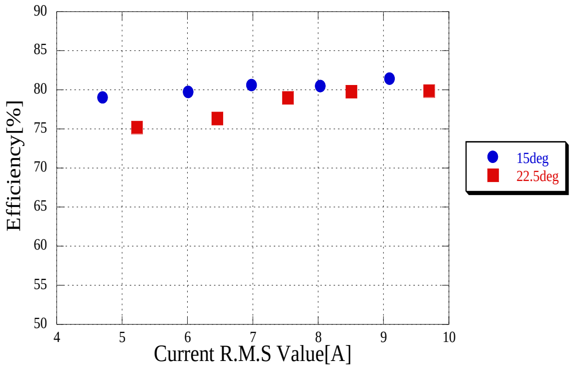
4.4 Efficiency characteristics

Figs. 14 (a) and (b) show the RMS current–efficiency characteristics. Though the efficiency of 22.5 degree is low on small current region, it becomes same value as that of 15.0 degree on large current region.

The efficiency of the 3-phase segment type SRM was about 77 % in Fig. 4. That of the 4-phase segment type SRM is about 80 %.



(a) 600 rpm



(b) 1800rpm.

Fig. 14. Efficiency characteristics

5. Conclusion

A 4-phase segment type SRM is proposed for reducing the torque ripple. Experimental system is produced and tested under single phase excitation control as well as two phases excitation control. It is confirmed that the torque ripple is decreased well under two phases excitation control. The maximum efficiency of the 4-phase segment type SRM is nearly 80%.

References

[1] T. J. E. Miller, Ed., "Switched Reluctance Motors and their Control", Lebanon, OH: Magna Physics/Oxford University Press, 1993.

[2] T. J. E. Miller, Ed., "Electronic Control of Switched Reluctance Motors", ser. Newnes Power Engineering Series. Oxford, U.K.: Newnes, 2001.

[3] B. C. Mecrow, J. W. Finch, E. A. EI-Kharashi and A. G. Jack, "The Design of Switched Reluctance Motors with Segmental Rotors" in Conference Record of ICEM 2002 No. 336, 2002.

[4] J. Oyama, T. Higuchi, T. Abe, and N. Kifuji, "Novel Switched Reluctance Motor with Segment Core Embedded in Aluminum Rotor Block", IEEJ Trans. IA, Vol.126, No4, pp.385-390, 2005.

[5] J. Oyama, T. Higuchi, T. Abe, and K. Tanaka, "The Fundamental Characteristics of Novel Switched Reluctance Motor with Segment Core Embedded in Aluminum Rotor Block", Journal of Electrical Engineering & Technology, Vol. 1, No.1, pp. 58-62, 2006.

[6] T. Higuchi, Y. Nakao, T. Abe, "Characteristics of a Novel Segment Type SRM with 2-step Slide Rotor", in Proc. The 12th ICEMS, LS04D-2, 2009.

[7] T. Higuchi, K. Suenaga, T. Abe, "Torque Ripple Reduction of Novel Segment Type Switched Reluctance Motor by Increasing Phase Number", in Proc. The 12th ICEMS, LS03C-4, 2009.

[8] D. Yamaguchi, T. Higuchi, T. Abe, Y. Yokoi, "A Characteristic Experiment of 4-Phase Segment Type Switched Reluctance Motor", in Proc. The 15th ICEMS, LS5B-3, 2012.

Tsuyoshi Higuchi received Ph.D. degree from Kyushu University, Japan in 1983. He is currently a Professor of Nagasaki University, Japan. His research interests are analysis, design and control of linear and rotary machines such as switched reluctance motors and permanent magnet motors. He is a member of IEEE and IEE of Japan.

Daiki Yamaguchi received M.E. degree from Nagasaki University in 2013. His research interest is motor drive. He is currently a regular employee of Toyota Motor Corporation.

Takashi Abe received Ph.D. degree from Nagasaki University in 2005. From November 1991 to July 1992, He was a Visiting Researcher at Politecnico di Torino, Italy. He is currently an Associate Professor of Nagasaki University. He has been active in the fields of electrical machine drive and power electronics. He is a member of IEEE, IEE of Japan, Society of Automotive Engineers of Japan and Japanese Society for Medical and Biogical Engineering.

Yuichi Yokoi received Ph.D. degree from Kyoto University, Japan in 2011. He is currently a Assistant Professor of Nagasaki University. His research interests include the technological application of nonlinear dynamics and the design of electrical machines. He is a member of IEEE, IEE of Japan, IEICE, and ISCI.