

Rotor Design to Improve Starting Performance of the Line-start Synchronous Reluctance Motor

Tae-Uk Jung[†] and Hyuk Nam*

Abstract - A single-phase line-start synchronous reluctance motor (LSSynRM) has merits of low cost, high efficiency and reliability. LSSynRM has an unbalanced magnetic circuit caused by flux barriers and various shapes of conductor bars when starting. Thus the motor may generate unstable starting torque in accordance with the initial starting position of the rotor.

This paper presents the rotor design to improve starting performance of the LSSynRM. Design variables are the number and the shape of the conductor bars. This design result is compared with the initial prototype and single-phase induction motor.

Keywords: Conductor bar, Flux barrier, Line-start synchronous reluctance motor(LSSynRM), Starting torque

1. Introduction

The capacitor-run single-phase induction motor (SPIM) is widely used in household appliances because of easy application and low cost. Nowadays, the need for a high efficiency motor for household appliances is continuously increasing because of international energy regulations.

Currently, the efficiency level of the SPIM is almost saturated and efficiency improvement is difficult and limited because rotor copper loss is comparatively large compared with other motors using the permanent magnet [1, 2].

Recently, many new ideas concerning motor structure and torque generation principle are added to the SPIM in order to improve efficiency. The single-phase line-start synchronous reluctance motor (LSSynRM) is a relatively newer idea.

In the LSSynRM the structure is almost identical to the SPIM except for the addition of flux barriers to the rotor core. This motor starts up by the help of induction torque from the rotor conductor bar cage like the SPIM. When the motor reaches synchronous speed it is rotated by synchronized reluctance torque due to the flux barrier, which makes the difference of inductance between the d-axis and q-axis. Because the motor rotates at synchronous speed to the rotating stator flux speed the induced current of the rotor conductor is very small. Thus the rotor copper loss is significantly reduced and the efficiency can be improved compared with the SPIM [3, 4].

Therefore, the LSSynRM would be a great new economic solution for the high efficiency single phase motor for household appliances.

So far the availability of the LSSynRM is recognized but sufficient design study has not yet been carried out. First of all, the assurance of starting stability is the most important issue because this is a line start type motor.

In the LSSynRM, the rotor flux barrier generates synchronized reluctance torque at synchronous speed, but this also generates unstable negative torque when the rotor is not synchronized with the rotating stator flux axis. The phenomenon is very serious during the starting stage.

When the LSSynRM is starting, unstable starting torque ripple and negative torque occurs according to rotor position because reluctance torque is not synchronized with the stator flux. Thus the motor cannot be accelerated and would fail to start in the end.

As above, the flux barrier generates reluctance torque for rotating at steady-state, on the other hand it has negative influence on starting. So we should trade off these 2 performances in the rotor design.

In this paper, rotor design is studied for the stable starting characteristics and high efficiency synchronous driving.

This study is focused on design optimization of the rotor to improve starting. The number and the shape of the conductor bars are determined as design variables. Maxwell 2D is utilized for finite element analysis and the suggested design model is made as a prototype and tested.

2. Structure and Characteristics of the LSSynRM

The LSSynRM has a very similar structure of induction

[†] Corresponding Author: Gwangju Research Center, Korea Institute of Industrial Technology (KITECH), Korea. (tujung@kitech.re.kr)

* Research Lab., Digital Appliance Company, LG Electronics Inc., Korea. (hnam@lge.com)

motor except for the flux barrier of the rotor core. Fig. 1 shows the cross-section of the LSSynRM.

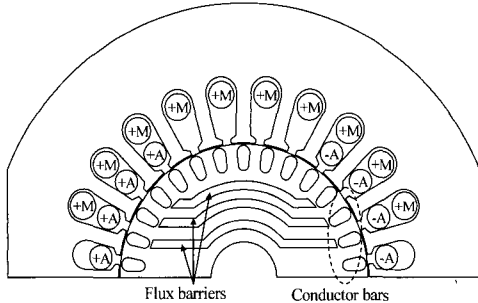


Fig. 1. Structure of LSSynRM

The symbols “M” and “A” represent the main winding and the auxiliary winding respectively. These windings are displaced with each other by the electrical angle of 90 deg. Driving circuit and winding connection are the same as those in the capacitor-run type SPIM. In the rotor there is a flux barrier for the reluctance torque and a conductor bar to allow the induction torque to start up.

2.1 Synchronous Speed Driving

In the synchronous speed driving condition, the flux barrier causes a reluctance difference between the d-axis and q-axis. Fig. 2 shows flux distribution characteristics according to flux flow path d and q-axis.

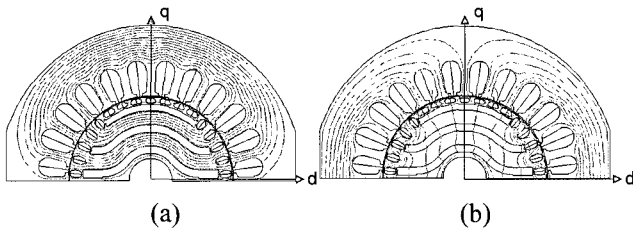


Fig. 2. Stator flux distribution (a) d-axis, (b) q-axis

In Fig. 2(a) stator flux flows into the rotor and along to the rotor core rib between flux barriers. This is the flux path of the d-axis and the reluctance is small. But Fig. 2(b) presents q-axis flux distribution. We can see that flux is blocked by flux barriers and only leakage flux due to the web and bridge between the bar and flux barrier crosses the rotor. In this case q-axis reluctance is large. By this reluctance, the difference of d and q-axis reluctance torque is generated. The torque equation is written as follows.

$$T = \frac{m}{2} \cdot \frac{P}{2} \cdot (L_d - L_q) \cdot \frac{1}{2} i_a^2 \cdot \sin(2\sigma) \quad (1)$$

Where, m is phase number and $m=2$ in this case, L_d is d-axis inductance, L_q is q-axis inductance, P is pole number,

σ is power angle between stator flux axis and rotor d-axis, and i_a is $\bar{i}_{main} + \bar{i}_{aux}$.

As written in Eq. (1) synchronous torque is proportional to inductance difference ($L_d - L_q$) or saliency ratio (L_d/L_q).

2.2 Starting Characteristics

Starting torque production is similar to that of the induction motor. But induction torque for starting is not stable unlike the induction motor.

Any flux that crosses the rotor core becomes distorted by an unbalanced magnetic circuit because of the flux barrier. It has bad influence on the starting induction torque.

Therefore the designs of the conductor bar and flux barrier are very important to endure both the induction torque and the reluctance torque.

Fig. 3 shows the typical speed-torque curve of the LSSynRM. The starting (locking) torque of zero speed and synchronizing torque around synchronous speed are the most important torque characteristics.

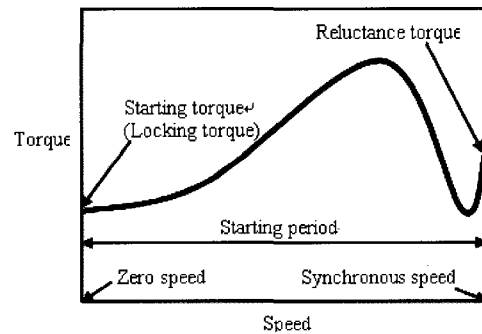


Fig. 3. Typical speed-torque curve of the LSSynRM

As a result, synchronous torque is dependent on flux barrier design and starting characteristics are mainly dependent on rotor conductor bar design.

3. Rotor Design for Starting Stability

3.1 Decision of the Number of Conductor Bars

In the SPIM the slot combination of the stator and rotor affects the starting characteristics even though there are no flux barriers. Therefore it is also very important to decide the number of conductor bars in the LSSynRM.

This paper analyzed starting torque characteristics of 4 models of Fig. 4 to find the appropriate number of conductor bars. The rotor conductor bar number of the conventional SPIM is 33. It's been determined as the optional value because the LCM with 24 slots of the stator is the maximum, and it's also been verified in an actual test.

But, in the LSSynRM, an odd number of conductor bars is difficult to be applied because rotor structure would be unsymmetrical. So we analyzed the even number of rotor conductor bar models, selecting those for considering the symmetric rotor structure with flux barriers. Those are 30, 32 and 34 number models near number 33, which is the number of the SPIM. In Fig. 4 only model(c) is a full model because the bar number is odd, and other models are analyzed as half models.

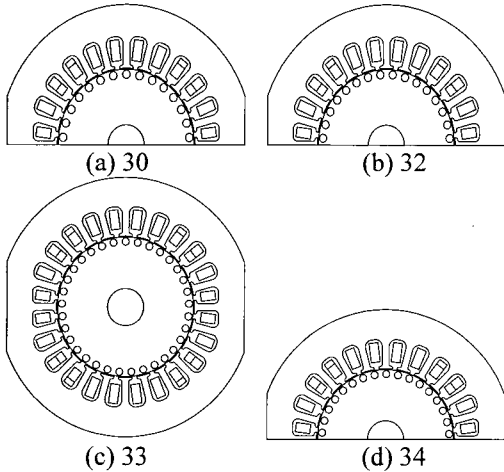


Fig. 4. Analysis models of various numbers of conductor bars

These analysis models don't have a flux barrier. The resistance of each conductor bar is uniform and skew effect is not considered. The rotor position shown in Fig. 4 is the initial position of 0 degrees and analysis is performed at 0, 4 and 8 degrees. Because rotor and stator have magnetic periodicity whenever the rotors rotate about 10 degrees, it is assumed that the rotor is locked and AC voltage power is applied to stator winding.

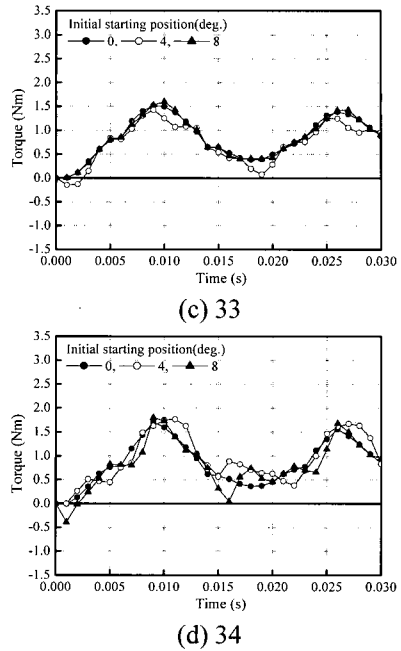
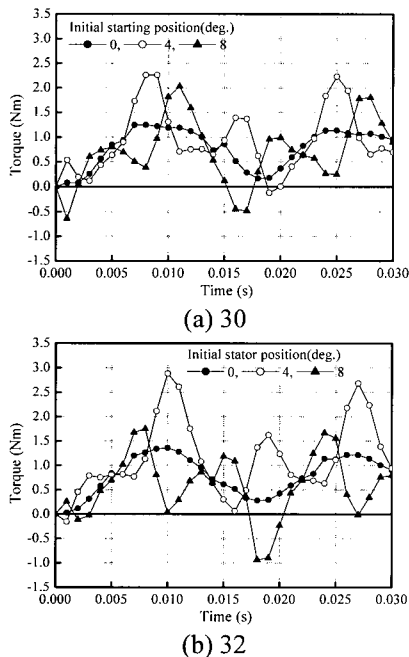


Fig. 5. Instantaneous starting torques according to the number of conductor bars

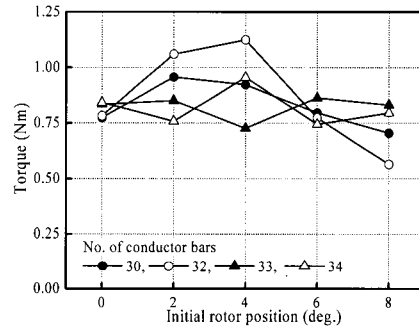


Fig. 6. Average torques of the instantaneous starting torque of Fig. 5

Fig. 5 and Fig. 6 are the results of the starting torque analysis by finite element (FE) analysis. As shown in the figures the starting torque of 30 and 32 bars is oscillated severely. The torque of 33 bars is almost equivalent value.

In the case of the LSSynRM, the conductor of even number is suitable because the motor requires symmetric magnetic circuit considering flux barrier. The torque variation of 34 bars is smaller than that of 32 bars and it is a little bit larger than that of 33 bars. Thus, the rotor conductor number is defined as 34 in this paper.

3.2 Torque Characteristics by the Shape of Conductor Bars

Fig. 7 presents the analysis model having the various shapes of the conductor bars and the zero initial starting position.

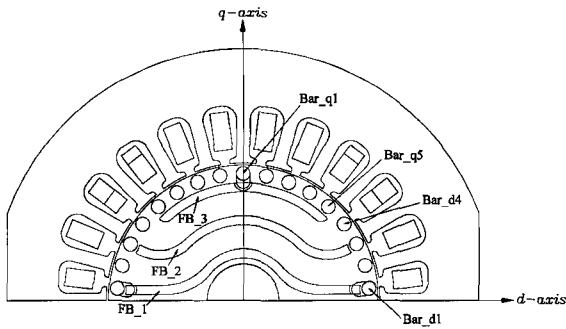


Fig. 7. Analysis models for the shape of conductor bar

This model has 34 conductor bars and 3 flux barriers. D-axis conductor bars are notated as Bar_d1 to Bar_d4 in order from d-axis in counterclockwise direction. In the same manner q-axis conductor bars are notated as Bar_q1 to Bar_q5 from q-axis in clockwise direction. Flux barriers are notated as FB_1 to FB_3 from shaft to air-gap.

In Fig. 7 let's assume that the conductor bars are the same shape and there is no flux barrier. This means that it is operated as the SPIM. The average starting torque, which is calculated each 10 deg. by FE analysis, is shown in Fig. 8 and 0.65 Nm is normalized as 100%.

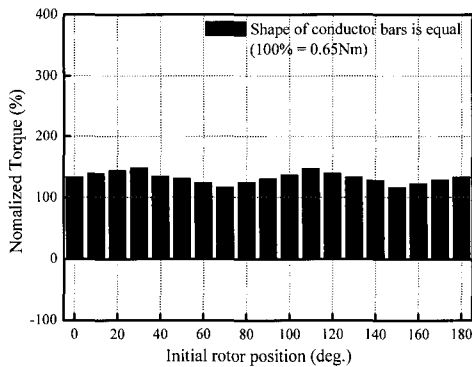


Fig. 8. Average starting torques when the analysis models of Fig. 7 are operated as induction motors

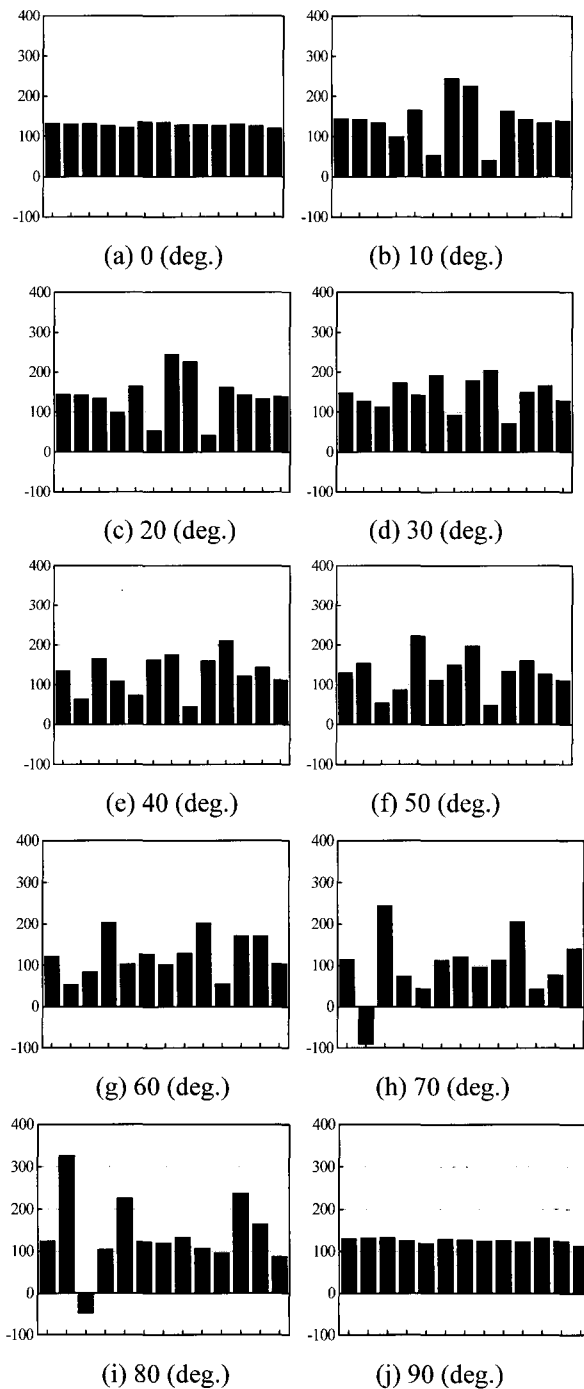
As shown in Fig. 8, if there are no flux barriers, this model has good self-starting characteristics.

However, in real cases, starting characteristics are deteriorated by the addition of the flux barrier. This paper analyzed starting characteristics according to the shape change of each conductor bar and the addition of each flux barrier in Fig. 7. This analysis result is presented in Fig. 9 and it is compared with the starting characteristics of Fig. 8 as a reference.

In Fig. 9 horizontal axis is Ref, Bar_d1, Bar_d2, Bar_d3, Bar_d4, Bar_q1, Bar_q2, Bar_q3, Bar_q4, Bar_q5, FB_1, FB_2 and FB_3 in order. Vertical axis is the normalized torque.

'Ref' means the value of Fig. 8 according to each rotor

angular position when this motor is operated as the SPIM having uniform conductor bar and no flux barrier. 'Bar_dn' means that the d-axis conductor bar of n order is only enlarged twice that of the original area as shown in Fig. 7 and the other bars including q-axis conductor bars are fixed as original shape and area. Further, 'Bar_qn' also means that the q-axis conductor bar of n order is only enlarged twice more than the original area. The other bars are fixed in their original shape and area. In addition, 'FB_n' means that the flux barrier of n order is added in the rotor.



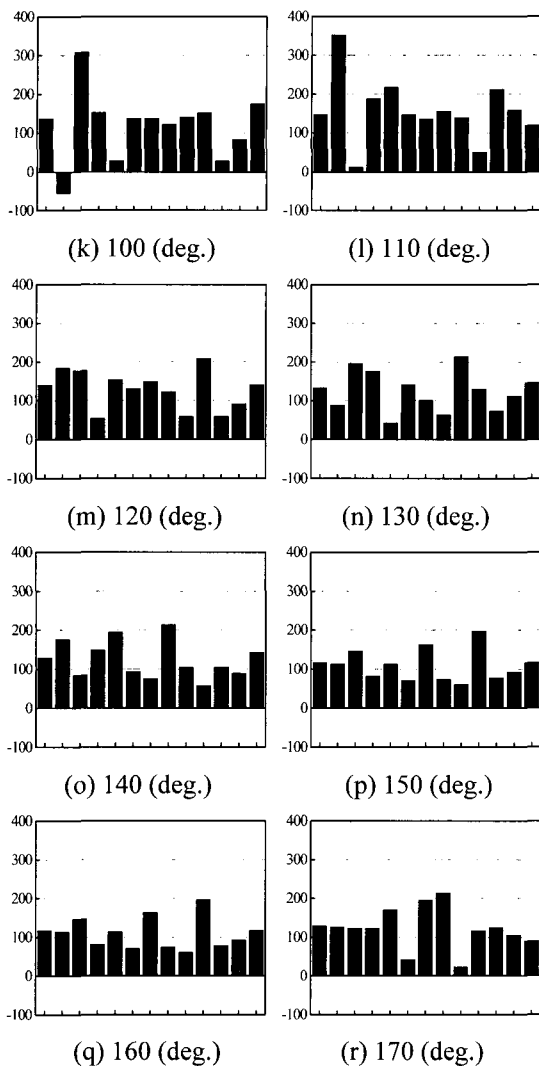


Fig. 9. Analysis results of the average starting torque according to initial starting position

As shown in Fig. 9 when d-axis bar Bar_d1 is increased this bar causes negative starting torque of 70 degrees although this bar increases the starting torque of 80 degrees.

On the contrary, if d-axis bar Bar_d2 is increased negative starting torque is generated at 80 degrees even though starting torque of 70 degrees is increased. Consequently, if Bar_d1 and Bar_d2 are increased at the same time the motor would generate positive starting torque at both 70 degrees and 80 degrees.

Flux barriers FB_1 and FB_2 give bad influence on the initial starting positions of 70, 100 and 120 degrees. The influence by FB_3 is smaller than FB_1 and FB_2. The most influent flux barrier is FB_1 because this barrier is located at an important position which can block almost all flux lines that are flowing into the rotor core.

The rest of the conductor bars and flux barriers also display similar characteristics. As such it's very important

to design flux barriers and conductor bars for good starting performance regardless of initial starting angular position.

Generally flux barrier design is mainly focused on normal synchronous driving performance. Therefore the design optimization of the conductor bar is a main design factor for starting performance.

4. Design Result and Comparison

The rotor of Fig. 7 is redesigned through many iterative analyses like Fig. 9 considering all combinations of each bar's area and shape. The specification of the stator is not changed.

The redesigned and improved rotor diagram is shown in Fig. 10 and the brief specification is written in Table 1.

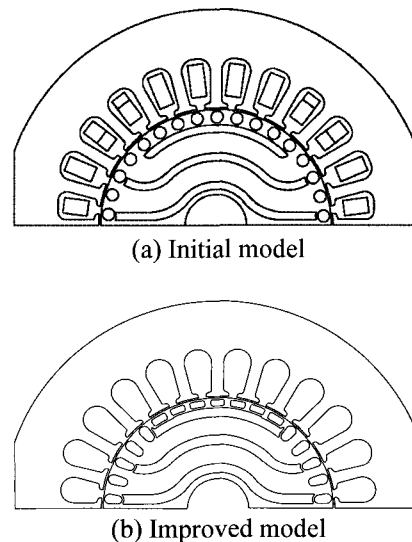


Fig. 10. Cross-section of initial and improved model

Table 1. Brief specification of the designed LSSynRM

Item		Initial model	Improved model
Voltage (V) / Frequency(Hz)		115 / 60	
Winding turns	No. of Main winding turn	139	
	No. of Aux. winding turn	180	
	Winding ratio	1.36	
Stator	Outer Dia. (mm)	110	
	Inner Dia. (mm)	61	
Rotor	No. of conductor	34	
	Conductor resistance (%)	100	81
	No. of flux barrier	3	3
	Saliency ratio k_w	0.70	0.74

Where, k_w is the ratio of flux barrier width to iron sheet rib width. In the improved model saliency ratio is increased, meaning that synchronous reluctance torque is increased.

The conductor bar area of the improved model is determined as shown in Fig. 11.

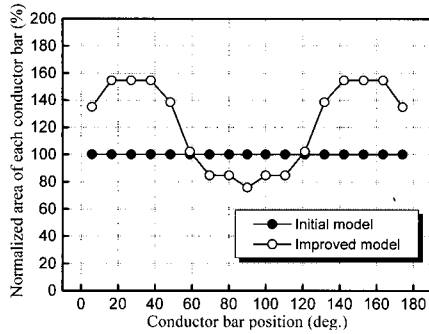
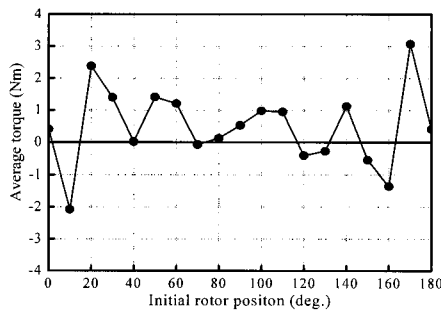


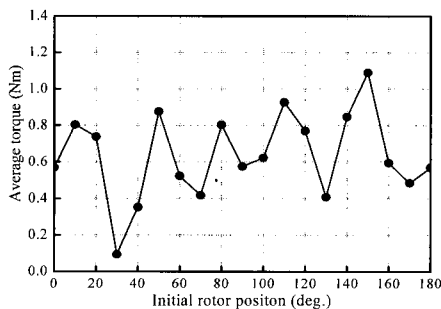
Fig. 11. Normalized area of each conductor bar

Conductor bar area distribution of the improved model is similar to the sinusoidal waveform. And the q-axis bar is designed to be flat and long in shape along the d-axis direction in order to ensure sufficient d-axis flux flow path as shown in Fig. 10(b). It's helpful to increase inductance difference between d-axis and q-axis.

Fig. 12 reveals the average starting torque of two models. The improved model generates positive starting torque at all starting positions, and we can see the improvement compared with the initial model. But the starting torque of 30, 70 and 130 degrees is smaller than that of other angles so it would be improved even more.



(a) Initial model



(b) Improved model

Fig. 12. Average starting torque comparison

Fig. 13 shows the speed-torque characteristics of the starting process. We can see the starting characteristics of the improved model. The initial starting torque is increased and the crawling torque due to unsynchronized negative reluctance torque is absent during the starting period.

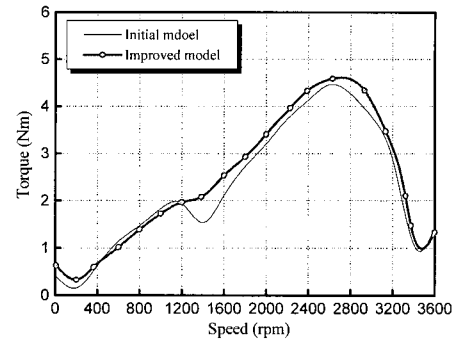


Fig. 13. The comparison of speed-torque characteristics

Table 2 displays the test results of the improved prototype LSSynRM and the SPIM at the same frame size. The performances are tested at the same rated torque of 2.2 Nm.

Table 2. Test results at rated driving

Item	SPIM	LSSynRM
Torque (Nm)	2.17	2.23
Speed (rpm)	3434	3600
Output power (W)	780	841
Input power (W)	925.9	966.2
Power factor (%)	96.8	96.0
Efficiency (%)	84.3	87.0
Stator copper loss (W)	62.0	82.0
Total loss – stator copper loss (W)	83.4	43.6

As shown in the table, the output power of the LSSynRM is larger than that of the SPIM because speed is increased to synchronous speed at the same rated torque. Thus, stator copper loss of the LSSynRM is larger than that of the SPIM. However, the other losses including rotor copper loss and core loss are very low. This result is due to the remarkable reduction of rotor copper loss because there is no slip of rotor speed and very low induced current of rotor conductor bar in the LSSynRM.

On the other hand, the irregular conductor bar distribution may cause additional losses due to harmonics in the SPIM. But its influence is very low in the case of the LSSynRM because the rotor is synchronized with rotating stator flux and the induced current of the rotor conductor bar is very small.

Therefore, the efficiency is improved by 2.7% compared with the SPIM. This result means that the LSSynRM is

useful in high efficiency topology as a single phase motor if starting stability is ensured. The LSSynRM is an appropriate motor for fans, pumps and other application starting conditions are not severe.

5. Conclusion

This paper dealt with rotor design to improve the starting performance of the LSSynRM. The appropriate conductor bar number is decided by the starting torque analysis according to the rotor conductor bar number. As well, the shape and the area of each conductor bar are designed to obtain the even starting torque regardless of initial starting position.

As a result, the designed LSSynRM has improved self-starting capability and its efficiency could be improved largely compared with the same frame size SPIM.

In the future, we would like to study the efficiency improvement design of the LSSynRM at steady-state considering noise reduction.

References

- [1] H. Murakami, Y. Honda, H. Kiriya, S. Morimoto, and Y. Takeda, "The performance comparison of SPMSM, IPMSM and SynRM in use as air-conditioning compressor," in *Conf. Rec. the 34th IAS Annual Meeting*, vol. 2, pp. 840-845, Oct. 1999.
- [2] H. Nam, K. H. Ha, J. J. Lee, J. P. Hong, and G. H. Kang, "A study on iron loss analysis method considering the harmonics of the flux density waveforms using iron loss curves tested on Epstein samples," *IEEE Trans. Magn.*, vol. 39, no. 3, pp. 1472-1475, May 2003.
- [3] I. Boldea, Z. X. Fu, and S. A. Nasar, "Performance evaluation of axially-laminated anisotropic (ALA) rotor reluctance synchronous motors," *IEEE Trans on Industrial Application*, vol. 30, no. 4, pp. 977-985, July/August 2003.
- [4] H. Kiriya, S. Kawano, Y. Honda, T. Higaki, S. Morimoto, and Y. Takeda, "High performance synchronous reluctance motor with multi-flux barrier for the appliance industry," in *Conf. Rec. the 33th IAS Annual Meeting*, vol. 1, pp. 111-117, Oct. 1998.



Tae-Uk Jung

He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Busan National University, Busan, Korea, in 1993, 1995 and 1999, respectively. Between 1996 and 2005, he was a Chief Research Engineer with the Laboratory of LG Electronics, Korea. Since 2006, he has been with the Korea Institute of Industrial Technology as a Senior Research Engineer. His main research interests are high efficiency motor design, control and application.



Hyuk Nam

He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Changwon National University, Changwon, Korea, in 1999, 2001 and 2004, respectively. Since 2004, he has been with the Laboratory of LG Electronics, Korea, where he is currently a Senior Research Engineer and engaged in research on high efficiency motor design and application.