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

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Abstract: - A single-phase line-start synchronous reluctance motor (LSsynRM) has an unbalanced magnetic circuit due to flux barriers, and various shape or size of conductor bars. Thus, unbalanced starting torque can be caused by depending on initial starting position. This paper presents a rotor design of a LSsynRM to improve starting performance of a prototype, which is fabricated as a device of household appliances. The design variables are the number and the size of the conductor bars in the rotor. The motor characteristics are analyzed by finite element analysis (FEA). The proposed model is manufactured, and the test results are compared with those of prototype.

Key-Words: - Finite element analysis (FEA), Household appliance, Line-start reluctance motor (LSynRM), Unbalanced starting torque

1 Introduction

A single-phase line-start synchronous reluctance motor (LSsynRM) has both conductor bars and flux barriers in the rotor. In transient state from start to reach synchronous speed, the motor characteristics are determined by conductor bars, and the characteristic profile has an irregular form as shown in Fig.1. After reaching synchronous speed, LSsynRM operates as a synchronous reluctance motor, and the characteristics are determined by flux barriers which cause the difference between d-axis inductance (L_d) and q-axis inductance (L_q). Therefore, the conductor bar loss is significantly reduced in steady-state so that it is possible to improve efficiency compared with a capacitor-run single phase induction motor (SPIM) [1]. Also it is possible to start without extra starting equipment, and therefore, the simple structure causes cost effeteness. To increase high saliency ratio (L_d/L_q) and high inductance difference (L_d-L_q), L_d should be increased or L_q should be decreased. In the design aspect, increasing L_d is more efficient than decreasing L_q. When the d-axis flux flows sufficiently, L_d is increased, and it is able to be obtained from reducing size of q-axis conductor bars vertically. On the contrary, size of d-axis conductor bars should be increased to reduce the conductor bar loss induced by the unbalanced rotating magnetic field.

When a LSsynRM has different size conductor bars because of above reasons, unbalanced locking torque is occurred in starting point depending on a rotor position, and it makes irregularly starting difficult [2]. Therefore, this paper deals with a rotor design of LSsynRM to improve starting performance and efficiency for household appliances. Design variables are the number and the size of the conductor bars. The process of the analysis is as follows.

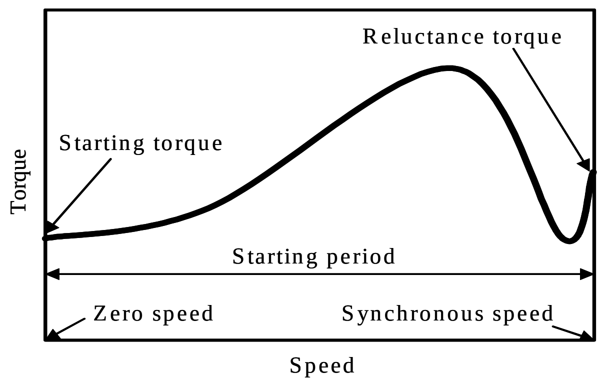

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Fig.1 Torque vs. speed of LSsynRM

Firstly, the number of the conductor bars is decided to obtain uniform starting torque regardless any initial starting position.

Secondly, starting torque is analyzed according to sizes of the conductor bars without considering flux barriers. After selecting the proper size, the effect of the flux barriers is considered in analysis. Finally, the size of the conductor bars are designed in detail to satisfy the uniform starting torque with initial starting position, and improve the efficiency in the steady-state.

2 Structure and Characteristics of LSynRM

Fig.2 shows the cross-section of the LSsynRM. The total slot number of the stator is 24, and main and auxiliary windings are arranged as shown in the figure. The symbols, “M” and “A” represent the main windings and the auxiliary windings, respectively. These windings are distributed by 90 electrical degrees difference in space. In the rotor, there are several flux barriers and conductor bars. The conductor bars in the q-axis flux path are called q-axis conductor bars, and the conductor bars in the d-axis flux path are called d-axis conductor bars in this paper.

Fig.3 displays the connection of the stator winding. The phase difference between two winding currents is occurred by means of a capacitor C_R connected with the auxiliary windings in series. The starting and running characteristics of the motor can be improved by changing the capacitance.

Table 1 represents the brief characteristics of the LSsynRM. As shown in the table, the motor has both induction torque by conductor bars and reluctance torque by flux barriers. Because of the flux barriers, the magnetic circuit becomes unbalanced and the unbalanced magnetic circuit has a bad influence on the induction torque. As the results, the conductor bars of the motor can induce the unbalanced starting torque according to the initial starting position of the rotor.

The conductor bars generate the induction torque. However, in the LSsynRM, the bars make obtaining sufficient L_d-L_q and L_d/L_q difficult [3]. Therefore, it is very important to design the conductor bars and the flux barriers considering both the induction torque and the reluctance torque.

3 Conductor Bar Design

3.1 Decision of the number of the Conductor Bars

In the case of the induction motor having the squirrel-cage rotor, the slot combination of the stator and the rotor affects the starting characteristics, even though the motor has no the flux barriers. Therefore, it is very important to decide the number of the conductor bars. Fig.4 shows the analysis models according to the number of the conductor bars, which is 30, 32, 33, and 34, respectively. It is assumed that the models have same magnetic material, shape, and dimension. The analysis models have no flux barriers, and the conductor bar resistances are uniform to avoid the difference of the torque magnitude. The skew effect is not considered in this paper.

When the rotor position in Fig.4 is defined as initial rotor position of zero, which is degree for starting from the speed of zero, the analysis is performed at two-degree intervals from zero to eight.

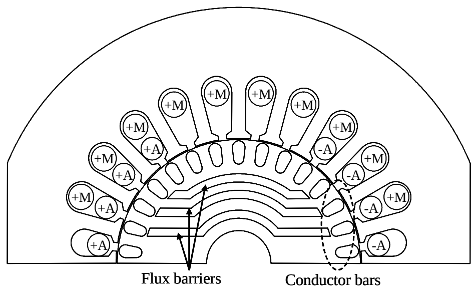


Fig.2 Cross-section of LSsynRM

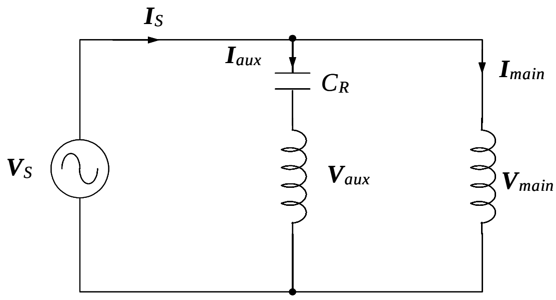


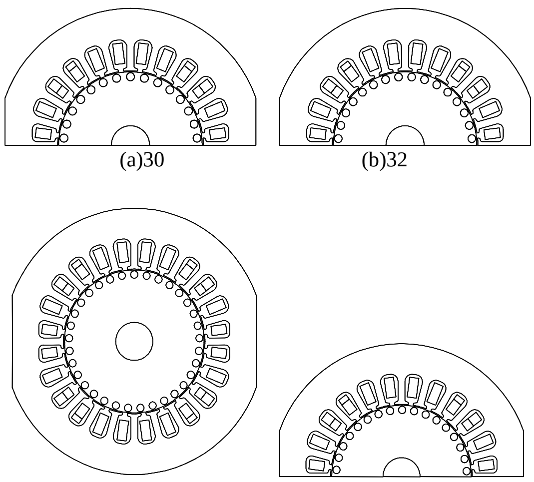
Fig.3 Stator winding connection of LSsynRM

TABLE 1
Brief Characteristics of LsynRM

Item	Induction torque	Reluctance torque
Principle	Conductor bars at asynchronous speed	Flux barriers at synchronous speed

Requirement	Uniform locking torque with initial rotor starting position	Increase d-axis flux and minimize q-axis flux to obtain L_d-L_q and L_d/L_q
Problems	Difficulty in uniform locking toque with initial rotor position by flux barriers	Difficulty in L_d and L_q by conductor bars

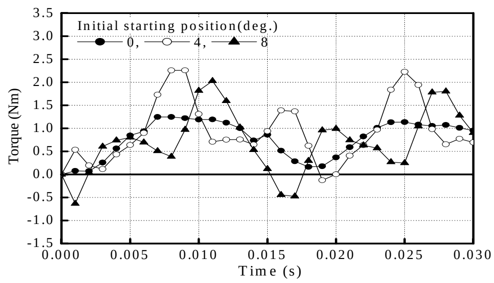
Fig.5 and Fig.6 are results of the starting torque analysis results by the finite element analysis (FEA) with the number of the conductor bars and the initial rotor position, when the speed is zero. As shown in the figures, the starting torque with 30 and 32 bars varies severely, whereas the torque with 33 bars has almost uniform value. The torque variation with 34 bars is smaller than that with 32 bars and is a little bit larger than that with 33 bars. In the case of the LSsynRM, an even number of the conductor bars is suitable because the motor requires the symmetric magnetic circuit. Thus, the rotor of the LSsynRM has 34 bars in this paper.



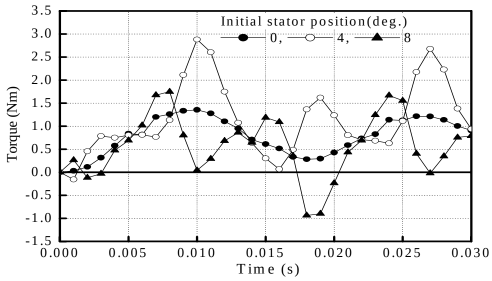
(a)30 (b)32

(c) 33 (d) 34

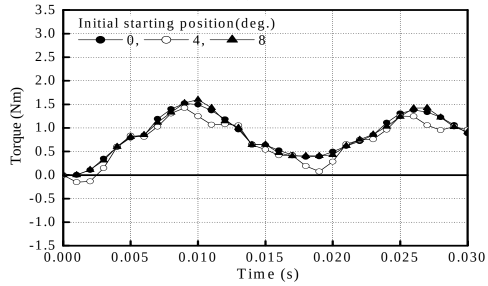
Fig.4 Analysis models with the number of conductor bars



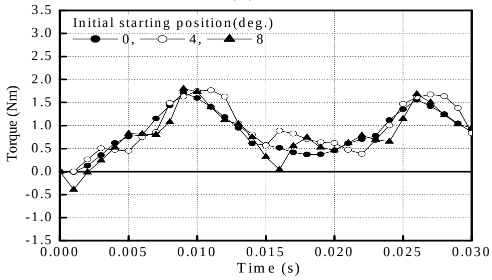
(a) 30



(b) 32



(C) 33



(d) 34

Fig.5 Instantaneous starting torques with the number of conductor bars and the initial rotor position at zero speed

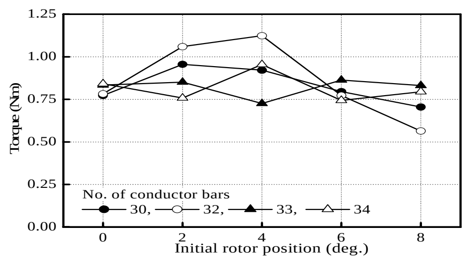


Fig.6 Average torques of the instantaneous starting torques in Fig. 4

3.2 Torque Characteristics with the size of the Conductor Bars

Fig. 7 presents the analysis models with the size of the conductor bars and the initial starting position is zero. The models have 34 conductor bars and 3 flux barriers. d-axis conductor bars are numbered from the center of d-axis in counterclockwise (CCW) direction. In the same manner, q-axis conductor bars are numbered from the center of q-axis in CCW direction,

flux barriers are numbered from the shaft in radial direction.

When the models in Fig. 6 is operates as induction motors under the same size of the conductor bars without the flux barriers, the average starting torques by FE analysis is shown in Fig. 8. The analysis is performed in ten-degree intervals form 0^0 to 180^0. The torque, 0.65 Nm is normalized as 100 %.

Fig. 9 displays the average starting torques with the size of the conductor bars and the flux barriers. From the left hand to the right hand, the values of the horizontal axis are named as Ref, Bard_1, Bard_2, Bard_3, Bard_4, Barq_1, Barq_2, Barq_3, Barq_4, Barq_5, Barr_1, Barr_2, Barr_3 in order. “Ref” means a SPIM which has uniform conductor bars. “Bard”, “Barq”, and “Barr” mean the d-axis bar, the q-axis bar, and the flux barrier, respectively. The area of the changed bar is twice larger than that of the original bar.

The values of the vertical axis are the normalized torque. Provided that size of the d-axis No.1 bar is increased, the bar causes negative starting torque at 70^0, even though the bar increases locking torque at that of 80^0.

On the contrary to the d-axis No.1 bar, that the d-axis No.2 bar is increased, the bar induces negative starting torque at 80^0, though the bar increases starting torque at the initial starting position of 70^0.

The size of q-axis No.1 bar is increased, whereas the bar reduces the starting torque at 10 and 20^0.

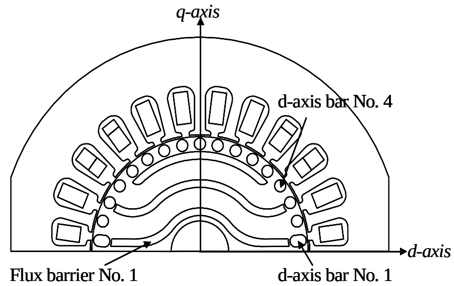
The flux barriers of No.1, and No.2 have an bad influence on the initial rotor position of 70, 100, and 120^0.

The rest of the conductor bars and the flux barriers also show the similar characteristics Therefore, it is very important to design flux barriers, and, especially, conductor bars for a good starting performance from uniform starting torque with the initial starting position.

4 Rotor design and Analysis Results

Fig.10 and Table 2 show the cross-section and the brief specifications of a prototype and a designed model of the LSsynRM, respectively.

Two kinds of models have identical stators. The stator lamination, stack length, winding’s effective turns are the same. The rotors of the models are different. While the prototype has 32 bars and 5 flux barriers, the designed model has 34 bars and 3 flux barriers. k_w, the ratio of flux barrier width to iron sheet rib width, of the former is 0/67, and that of the latter is 0.74.



(a) d-axis conductor bars and flux barriers

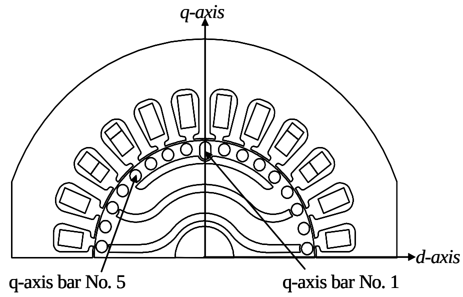


Fig.7Analysismodelswiththeshapeofconductorbars

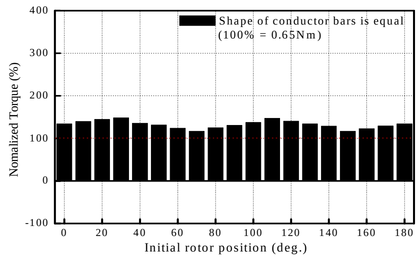
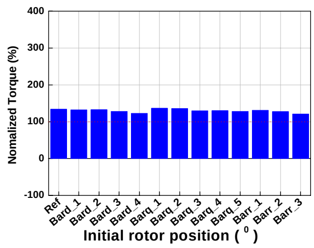
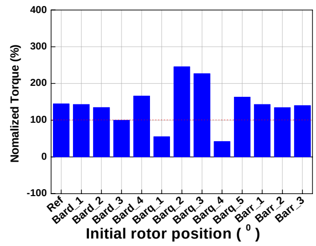


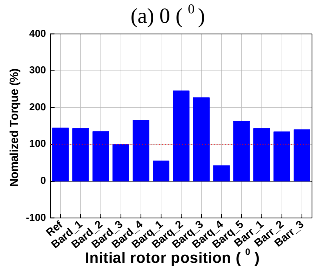
Fig.8 Average starting torques when the analysis models in Fig. 6 are operated as induction motors



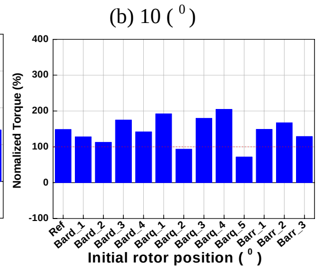
(a) 0 (^{0})



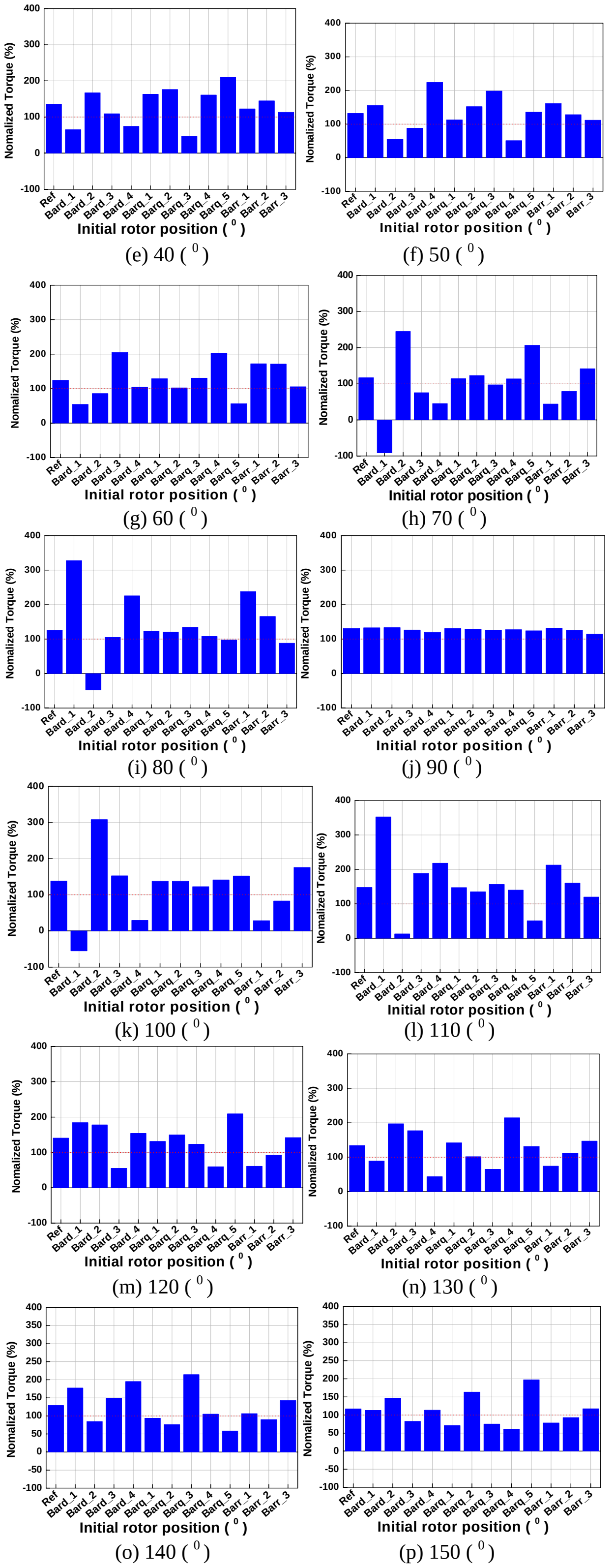
(b) 10 (^{0})



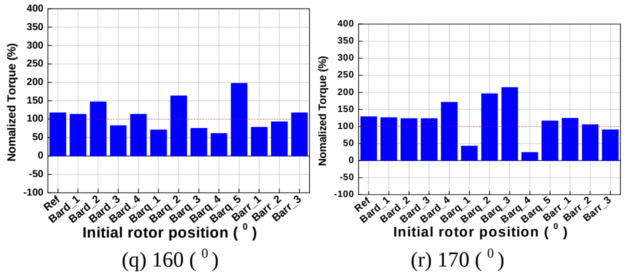
(c) 20 (^{0})



(d) 30 (^{0})



(e) 40 (0) (f) 50 (0)
(g) 60 (0) (h) 70 (0)
(i) 80 (0) (j) 90 (0)
(k) 100 (0) (l) 110 (0)
(m) 120 (0) (n) 130 (0)
(o) 140 (0) (p) 150 (0)



(q) 160 (0) (r) 170 (0)

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

Fig.11 indicates average starting torques. In Fig.11(a), the prototype has negative starting torque positions. Unlike this, the designed model generates positive starting torque all over the initial starting position even though the starting torques between 30^0 and 130^0 are smaller than in other degrees.

In Table 3, the steady state characteristic analysis results of the designed model are compared with those of the prototype. The rated torque and the rated output power are 2.26 Nm and 853 W, respectively.

As shown in the Table 3, the main and secondary copper losses of the designed model are larger than those of the prototype. It is because the main current and the conductor bar resistance of the former are larger than those of the latter. As the results, while the total conductor bar loss and the efficiency of the prototype are 83.23 W and 91.11 % respectively, those of the designed model are 90.25 W and 90.43 W, respectively. The iron loss is ignored.

5 Experimental Results

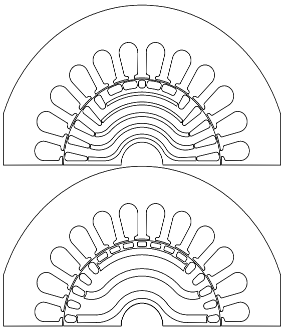
Table 4 is the experimental results of the starting performance of the compressor during starting period. In the table, there are three kinds of test conditions according to load of the compressor.

When the prototype is tested under the cooling condition, the motor is locked at certain position, though standard and overload conditions are satisfied. It is analyzed that the motor is locked at the initial starting positions which cause the negative starting torque in Fig.11(a). By contrast, the designed model can be started in the cooling condition as well as standard and overload conditions.

TABLE 2
Brief Specifications of the Designed LSsynRM

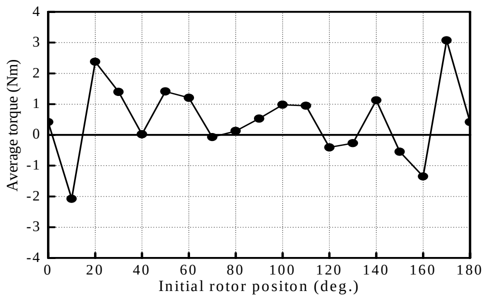
Item	Prototype	Designed model
Input voltage (V) / Frequency(Hz)	115 / 60	
Winding	The series turns of main winding is 139 The series turns of auxiliary winding is 180 The winding ratio is 1.36	

Stator		The ratio of the inner diameter and the outer diameter is 0.54	
Rotor	The number of conductor bars	30	34
	The resistance of conductor bars (%)	100	152
	The number of flux barriers	5	3
	k_w	0.67	0.74

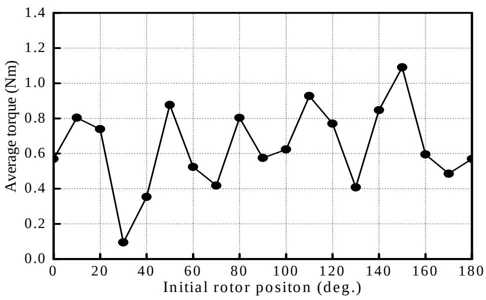


(a) Prototype (b) Designed model

Fig.10 Cross-section of the prototype and the designed model of the LsynRM



(a) prototype



(b) Designed model

Fig.11 Analysis results of the average starting torque of the prototype and the designed model

Table 5 summarizes the experimental results of the compressor at the steady-state when the torque is 2.20 Nm.

The efficiency of the designed model by FE analysis in Table 3 is lower than that of the prototype. However, the experimental results are reversed. It is analyzed that the conductor bar resistance of the prototype is larger than that of the designed model when the motors are manufactured.

6 Conclusions

This paper deals with the LSsynRM design to improve starting performance for household appliances.

From the starting torque analysis results with the number of conductor bars, the number of 34 conductor bars is chosen for the LSsynRM. In addition, the size of the bar is decided to obtain the starting torque with the initial starting position. By experimental results of both the starting performance and steady-state, it is confirmed that the designed model has a good self-start capability and characteristics in comparison with prototype.

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TABLE 3

Analysis Results at the Steady-state

Items		**Prototype**	**Designed model**
Rated torque (Nm)		2.26	2.26
Rated speed (rpm)		3,600	3,600
Rated output power (W)		853	853
Line current (A)		11.3	10.8
Main current (A)		7.41	7.66
Auxiliary current (A)		4.13	4.10
Efficiency (%) (Iron loss is ignored)		91.11	90.43
Copper loss	Main	42.28	45.18
	Auxiliary	30.53	30.09
	Secondary	10.42	14.98

Total conductor bar loss (W)	83.23	90.25
Maximum reluctance torque(Nm)	4.87	4.24

Table 4
Experimental Results of the Starting Performance

Item	**Prototype**	**Designed model**
Standard condition	Success	Success
Overload condition	Success	Success
Cooling condition	***Failure at certain position***	Success

Table 5
Steady-state Experimental results of the Compressor

Item	**Prototype**	**Designed model**
Torque (Nm)	2.18	2.23
Speed (rpm)	3600	3600
Power factor (%)	93.9	96.0
Efficiency (%)	85.2	87.0
1^{st} copper loss (W)	92.0	82.0
Total loss (W) -1^{st} copper loss (W)	50.7	43.6
Input power (W)	964.5	966.2