Design and analysis of an IE4 Class Line-Start Synchronous Reluctance Motor Considering Total Loss and Starting Performance

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In this paper, an optimum design for a three-phase line start synchronous reluctance motor (LS-SynRM) with respect to efficiency, maximum torque, and starting torque is proposed. The design variables, objective functions, and constraints are selected for this optimum design, which is divided into two steps. Step I maximizes the rated efficiency while maintaining a balanced operation and minimizing the stator copper loss. Step II calculates the precise starting torque using finite element analysis (FEA). The validity of the optimum design is verified by comparing the efficiency, maximum torque, and starting torque characteristics of the time-step FE analysis with experimental results.

***Index Terms*— Line start synchronous reluctance motor, Parameter design, Starting performance, Steady-State**

I. INTRODUCTION

THE LS-SynRM is capable of starting “across the line” by switching it to an AC voltage source. Once started, it runs at a synchronous speed. The torque is entirely determined by the load, which means the evaluation of the direct-on-line performance. To achieve higher reluctance ratios of the direct and quadrature axes, thereby generating larger torques [1], the rotors of the LS-SynRMs are specially designed to meet such objectives at specified physical constraints. Fig. 1 shows that the distances between the flux barriers (widths of the segments) are relatively small. Moreover, the shapes of the ribs and the additional ribs between the flux barriers and the rotor slots are important parameters for better performances [2]. However, in the manufacturing process of LS-SynRMs, the addition of cage slots will result in a more complicated rotor structure, while additional cage slots will form an inner rib with multi-barriers, resulting in an increase in leakage flux in the inner layer, the motor efficiency decreases.

Therefore, the feasibility of adopting an optimal design method and fabrication of an LS-SynRM was studied, as presented in this paper, with specific targets of high efficiency (Super premium level, IE4) and high torque. The optimal LS-SynRMs have characteristics suitable for mass production and easy manufacturing processes. Moreover, the optimal LS-SynRM is capable of greater torque per unit weight, the ratio factor (Ld/Lq), and the rotor inductance difference (Ld-Lq) along the d-and q-axes significantly, because of the optimal design in flux barrier and cage slots arrangement. In addition, the torque ripple characteristics, in consideration of the influence of the core magnetic saturation, are also analyzed by calculating the d-axis and q-axis inductances. The main design parameters of the rotor are the thickness of the magnetic flux barrier, the iron core and the presence of the rib. The proposed model is analyzed using the response surface method (RSM) coupled finite element method (FEM). Finally, the torque characteristics of the optimal design model are verified by comparing the finite element analysis simulation with the experimental results.

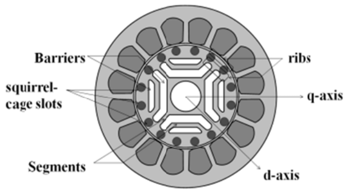


Fig. 1. Configuration of LS-SynRM

II. CHARACTERISTIC OF LS-SYNRM

The starting process of the LS-SynRM has the following two separate phases: asynchronous run-up and synchronization. The squirrel-cage rotor provides the asynchronous run-up torque, similar to SCIMs, starting at zero speed. As the speed approaches the synchronous speed, the slip tends to zero, and the LS-SynRM enters the synchronization phase. The cage torque can be expressed using (1).

$$T_c = K_T \Phi_m I_2 \cos\varphi_2 \qquad (1)$$

With the cage torque, Fig. 2 shows the typical torque/speed curve of the cage torque. For the LS-SynRM, the following two start conditions are included:

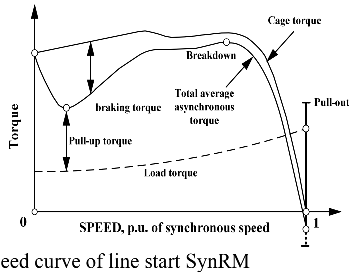


Fig. 2. Torque /speed curve of line start SynRM

A. Asynchronous operation and starting

An additional drag torque is generated because of the interaction of the saliency and the stator circuit. For speeds below the synchronous speed, the torque is called the pull-up torque, which is the minimum torque available for acceleration at any asynchronous speed. The saliency pull-up torque can be expressed using (2).

$$T_{sb} = -\frac{m}{2}\frac{V^2 pR_{ph}}{\omega}\frac{(X_d - X_q)^2}{[R_{ph}^2 + X_d X_q]^2} \qquad (2)$$

B. Steady state

Under balanced conditions, the steady state performance of the LS-SynRM can be expressed using (3).

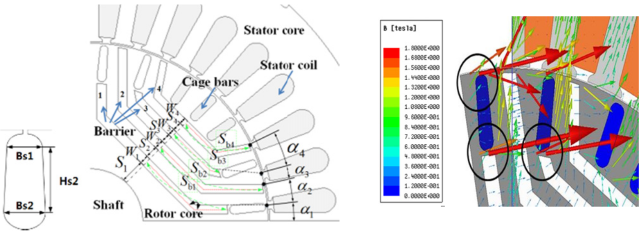
$$T_R = \frac{mp}{\omega}\left[\frac{V^2}{2}\left(\frac{1}{X_q}-\frac{1}{X_d}\right)\sin 2\delta\right] \quad (3)$$

Reluctance values in the d- And q-axis of LS-SynRM affect the starting torque and stated state torque. Therefore, it is important to design the rotor structure in accordance rotor cage slots (influences cage torque *Tc*) and the thickness of the magnetic flux barrier and the presence of the rib (influences pull-up torque T_{sb} and steadu state torque T_R) for high torque density. In addition to these rotor design variables, more design variables exist. However, in this paper, only these parameters are selected for optimizing the design with minimal analysis time.

III. PROPOSED MODEL AND OPTIMAL DESIGN

A. Basic model

The basic model of an LS-SynRM can be similar to the stator of an SCIM, and the rotor with squirrel– cage is shown in Fig. 3 and parameter listed in Table I.



(a) (b)

Fig. 3. (a) Position indications of related rotor parameters of the three phase four-pole LS-SynRM. (b) Flux leakage of LS-SynRM rotor

The rotor bar dimension has direct impact on the leakage flux of rib between multi-barriers and bars (Fig.3(b)). And result of basic model by FEM analysis is shown in Table II.

B. RSM

For examining the effect of main aim for independent torque and saliency maximization and leakage from the inner rib in LS-SynRM rotor design was developed which is shown in Fig.4 (a). The given design variables, including Multi-cage slots "length", are used in the RSM optimization. The responses of design objectives with all design variables are displayed in Fig.4(b) It is found the desired minimum points of core loss and maximize inductance ratio and inductance difference cannot be achieved at the same design point. Therefore, the optimum point is selected as possible as close to satisfy all design requirements, as each point of "cross lines" suggested. With satisfying all design objectives, the optimal rotor flux barriers/segments design LS-SynRM model is built using the corresponding values of design variables.

TABLE I

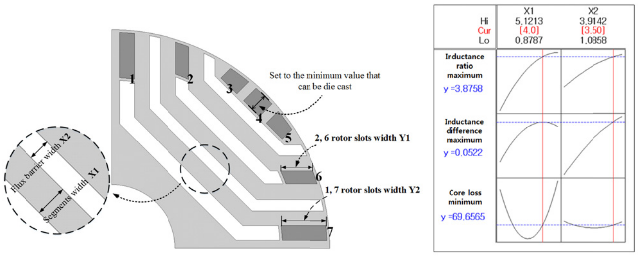
LS-SYNRM BASIC MODEL PARAMETER

Item	Unit	Value
Stator input voltage	V	380
Rated frequency	Hz	60
Number of stator/rotor slots/poles	-	36/28/4
Stator outer diameter	mm	192.5
Rotor outer diameter	mm	116.4
Air gap length	mm	0.5
Motor depth	mm	110
Rib width	mm	0.7
Rotor slots size	mm^2	31.25
Barriers 1-4 width	mm	3, 3, 2.3, 2.3
Segments 1-3 width	mm	4, 3, 3

TABLE II

LS-SYNRM BASIC MODEL PERFORMANCE (FEA) RESULT

Item	Unit	Basic model
Ia (phase)	Arms	9.37
Stator copper loss	W	177.5
Rotor copper loss	W	18.9
Iron loss	W	72.9
Power factor	-	0.66
Efficiency	%	90.26



(a) (b)

Fig. 4. (a)Design values of each design variable. (b)Response of design objectives based on design variables in RSM

IV. EXPERIMENT AND CONCLUSION

In the full text, we will fabricate and compare the efficiency and loss of the basic model and optimal design model through experimentation, as well as the startup problem. It is found that the model efficiency can reach (IE4) class by optimizing design.

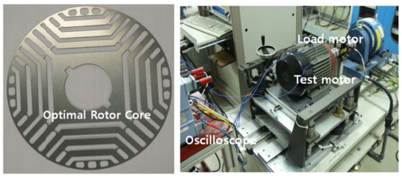


Fig.5. Optimal design rotor core and experiment set

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