Optimal Rotor Shape Design for Performance Improvement of Line Start Permanent Magnet Motor

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Recently Line Start Permanent Magnet Motor (LSPM) is a well-known motor due to its technical advantages in academic and industrial applications. The LSPM combines a permanent magnet rotor that allows higher motor efficiency during synchronous operation, and an induction motor squirrel cage rotor for starting the motor by connecting it directly to an A.C. Source. In this paper, we will deal with the performance improvement of a 3.7kW, 2-pole, three-phase LSPM using the difference in d-axis magnetic inductance (L_d) and q-axis magnetic inductance (L_q). Therefore, nonlinear finite element analysis is necessary to obtain the L_d and L_q. The performance improvement can be effectively achieved by designing optimization of the rotor structure using finite element method. The optimized slot shape of PM was selected for the prototype machine, which improves the efficiency and power factor of LSPM.

***Index Terms*— Line start permanent magnet motor, finite element analysis, Optimization.**

I. INTRODUCTION

Recently due to the demand of energy saving purpose, replacement of the line-operated induction motor (IM) by line start permanent magnet synchronous motor (LSPM) is of concern in academy and industry. LSPM has a higher efficiency than (IM) and an advantage in constant speed operation regardless of the effect of load variation. It has permanent magnets (PMs) buried bellow the squirrel cage in rotor, thus operates in steady state as conventional interior permanent magnet synchronous motor (PMSM). In this manner, it combines the advantages of induction motor (robust construction and line-starting capability) and PMSM (high efficiency, power factor). The line start permanent magnet motor (LSPM) is noted as alternative routes comparing with the induction motor that it offers high efficiency and unity power factor. [1]- [2]

In this paper, a 3.7 kW three phase LSPM was designed and optimized [3] for performance improvement. The specifications of the machine are given in Table 1. It is a three phase two pole machine, each pole has three pieces of PMs as shown in Fig. 1.

II. ANALYSIS OF STEADY STATE

Electromagnetic torque of LSPM machine expressed as:

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{pm} i_q - (\xi - 1) L_d i_d) i_q\right) \tag{1}$$

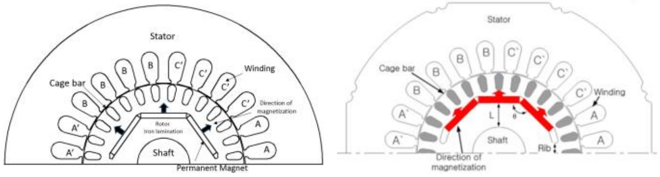
Where, i_d and i_q are the components of armature current. L_d and L_q are the d-axis and q-axis inductances, λ_m is the PM flux linkage and P is number of poles and ξ is saliency ratio.

$$L_d = \frac{\psi_0 \cos\alpha - \psi_a}{i_d},\ L_q = \frac{\psi_0 \sin\alpha}{i_q},\ \xi = \frac{L_q}{L_d}$$

The power factor and efficiency equations are given below.

$$PF = \cos(\varphi) = \cos\left(\tan^{-1}\left(\frac{\frac{L_d}{L_q}\frac{i_d}{i_q} + \frac{i_q}{i_d}}{\frac{L_d}{L_q} - 1}\right)\right) = (\xi - 1)\sqrt{\frac{\sin(2\alpha)}{2\left(\tan\theta + \xi^2 \cot\alpha\right)}}$$

$$\eta = \frac{P_{Out}}{P_{Out} + P_{Loss}} = \left(1 + \frac{1}{\frac{\omega_r}{3.R_{th}} \cdot \left(\frac{T}{I^2}\right)}\right)^{-1}$$



(a) (b)

Fig.1 . (a) Initial model (b) Optimal structure of modified LSPM model

TABLE I

DESIGN SPECIFICATION OF LSPM

Item	Value	Item	Value
Phase	3	Rotor Outer Diameter [mm]	87.8
Pole Number	2	Rotor Inner Diameter [mm]	25.4
Rated Torque [Nm]	9.1	Rotor bar number	28
Rated Speed [rpm]	3600	Rotor bar material	Al
Frequency [Hz]	60	Material of magnets	Nd-Fe-b
Stator Outer Dia. [mm]	159	Stack Length [mm]	90
Stator Inner Dia. [mm]	89	Br at 100°C [T]	1.21
Lamination [mm]	90	Hc at 100°C [KA/m]	7.35
Slots number	24	Thickness [mm]	3

Here, $P_{Loss}=3R_{th}I^2$, α is the current angle, I is the line current, T is the electromagnetic torque, R_{th} is total resistance, ω_r is the mechanical angular velocity, η is the efficiency of LSPM. Where, $i_d=-I_a \sin\beta$ and $i_q=I_a \cos\beta$.

III. OPTIMIZATION OF LSPM

The initial model of this machine is shown in Fig.1 (a), the analysis and experimental results have been reported in [5]. The block PM used in the original model has a thickness of 3 mm and length of 28 mm. Statistical experimental methods such as design of experimental (DOE) and response surface methodology (RSM) have been applied to optimize media for industrial purposes. Three design variables in this optimization process are chosen as illustrated in Fig. 1(b). Thickness of PM is fixed at 3 mm due to de-magnetization weakness during synchronization. Ranges of design variable are listed in Table II. Therefore, when the angle increases, the inverse relation-ship L, and Rib are reduced. The θ angle increases when the magnet and the value of L are reduced. Therefore power factor is getting higher as well as efficiency.

TABLE II

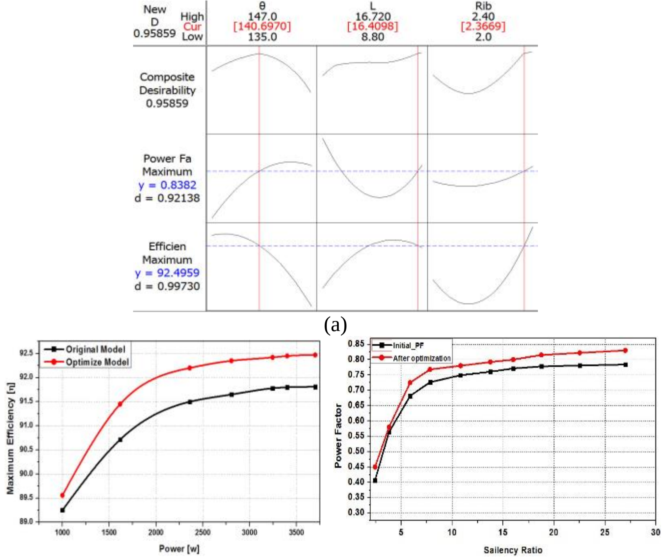
DESIGN VARIABLES AND EXPERIMENT RANGE FOR RSM

Design variable	Items of design variable	Experimental range	Unit
L	Length from PM slot to shaft	8.80~16.72	mm
θ	Slot angle of side PM segment	135°~147°	Deg.
Rib	Air duct gap	2 ~ 2.40	mm

First, design candidates with L, θ and Rib were studied by transient finite element analysis. The response surface of efficiency and power factor is given in Fig.2 (a). Optimum candidate L=16.40 mm, θ =141^0, Rib=2.37 are satisfied with the efficiency and power factor. With 85% amount of PM material and same aluminum material used in the original model, the final model of LSPM is analyze and manufactured according to the optimal PM design.

IV. VERIFICATION AND EXPERIMENTAL TEST

Based on optimal point, efficiency and power factor are compare with initial design are illustrated in Fig. 2(b), (c) respectively and results of computational optimization compared with the initial design are shown in Table III. These results compare very well with those obtained using FEA analysis directly.



(a)

(b) (c)

Fig.2 (a) Optimization analysis with RSM (b) Efficiency comparison between Initial model and optimized model (c) power factor Comparison between Initial model and optimized model

TABLE: III
COMPARISON BETWEEN INITIAL SHAPE AND OPTIMUM SHAPE

Parameter	Unit	Initial designed motor	Optimum designed motor
L	mm	8.80	16.40
θ	Deg.	135°	141°
Rib	mm	2.0	2.37
Power Factor	-	0.78	0.83
Efficiency	%	91	92.4

LSPM with optimized rotor has been prototyped for the experimental validation of the FEA results and the verification of the rotor optimization techniques. Experiment was set up to test the prototype motors using dynamo test bed as shown in Fig.4. Fig. 3 shows the photo of optimized rotor. Load test at rated speed (3600 rpm) are carried out by varying load factor from 0 to 140 [%]. Power, phase current, efficiency, PF and torque according to different load were recorded and summarized in Fig. 5 and FEM analysis and experimental data are almost identical as shown in Table IV.

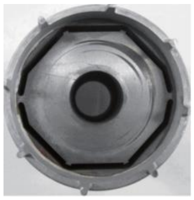


Fig.3 Optimized rotor.

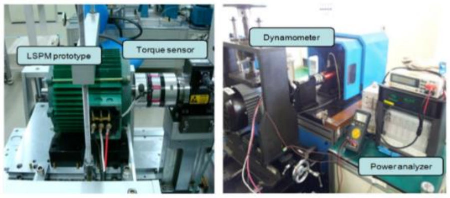


Fig.4 Dynamo setup to test of LSPM

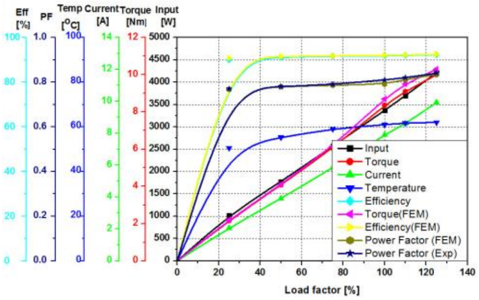


Fig.5. (a) Performance curves at rated speed

TABLE IV
COMPARISON BETWEEN EXPERIMENT AND FEM RESULT

Items	Unit	FEA Analysis	Experimental Analysis
Rated Voltage	V	380	380
Rated Current	A	10	10
Rated Speed	rpm	3600	3600
Torque	Nm	10.045	9.93
Power factor	-	0.84	0.83
Efficiency	%	92.45	92.37

V.CONCLUSION

This paper describes the development process of a 3-Phase 3.7kW 2-Pole LSPM by optimizing the rotor structure using response surface method. Two-dimensional transient finite element analysis was utilized for accurate calculation of efficiency, current, speed curve etc. The experimental results obtained from the prototype demonstrate satisfactory agreement with the estimated by FEA approaches, and underpin the findings of the study. And optimum design for the rotor are satisfied with the required motor specification.

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References

[1] M.A Rahman and T.M. Osheiba, "Performance of a large line start permanent magnet synchronous motor", *IEEE Trans. Energy Conversion*, vol. 5, pp.211-217, mar. 1990.

[2] T.J.E. Miller, "Synchronization of line-start permanent magnet AC motor," *IEEE Trans. Industry application*, vol. PAS-103, 1984, pp.1822-1828.

[3] F.J.H.Kalluf, C.Pompermaier and N.Sadowski, "Magnet flux optimization method for line start permanent megnet motors," *IEEE International Electric Machines and Drives*, May 2009, 953-957.

[4] C.A.da Silva, J.R. Cardoso and R. Carlson, "Analysis of a three-phase LSPMM by numerical method," *IEEE Trans. on Magn.*, vol.45, (March 2009), 1792-1795.

[5] J. Li and Y.H. Cho, "Design of high performance line start permanent magnet synchronous motor with high inertia load," *International Journal of Applied Electromagnetics and Mechanics 33* (1, 2) (2010), 621-628.