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Session PD2: Electrical machines and Drives V

10:40-12:10 – Room: Poster Session Room I

Estimation Technique of Magnet Reduction in Single-Phase Line-Start Permanent Magnet Motor with Double-layer Rotor Design

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This paper presents a study on magnet reduction in a single-phase line-start permanent magnet motor (LSPMM) without deteriorating motor torque and efficiency performances. For saving magnet material used in a prototype single-layer PM rotor design LSPMM model, the unique hybrid torque characteristic is utilized, that higher balance ratio of reluctance toque to magnet torque helps to lower the dependency on PM material usage. Therefore, a double-layer PM rotor design LSPMM model is designed to create higher rotor saliency ratio for increasing reluctance torque generation to compensate decreased magnet torque due to magnet reduction. The finite element analysis (FEA) coupled with equivalent circuit method is used to analyze the LSPMM performance, and test results confirmed the validity of the presented estimation approach.

***Index Terms*—Double-layer IPM rotor design, FEA, hybrid torque characteristic, LSPMM, torque and efficiency performance.**

I. Introduction

THE LINE-START induction motors (LSIM) are well known as their simplicity, rugged construction and relative lower manufacturing cost, as well as their line-start capability that being fed directly from the commercial single-phase voltage source without any type of control device [1]. However, their relative low efficiency performance can not satisfy the increasing demand of high-efficiency requirement. On the other hand, the interior permanent magnet synchronous motors (IPMSM) are attractive for their high efficiency and high torque density, but the IPMSM requiring an expensive inverter for operation [2].

The single-phase line-start PM motor (LSPMM), that has PM segments and inner air-gap regions buried into the caged rotor of IM, thus it can generate asynchronous starting torque by means of induction caged rotor, and utilizing hybrid torque at synchronously running, which guarantees high efficiency at steady state operation [3]. The LSPMM has beneficial attributes of both IM and IPMSM, is being developed as a high-efficiency alternative to the induction motor, that are widely used in household appliance, such as the compressor of air-condition and refrigerator.

However, these performance advantages are always negated by high cost of PM material. Although the price of PM is gradually decreasing, the reduction of magnet usage in PM machine design is always a practical objective. Therefore, an efficient approach for guiding PM usage reduction in IPM machine design is very expected, but few papers focused on it.

This paper presents an effective approach for estimating the possible reduction of magnet material in a LSPMM design. By assuming the enhancement of structure advantage in machine performance, the dependency on magnet material usage is gradually reduced, which can be easily estimated from the variation of basic machine characteristics.

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In this paper, the magnet reduction design focus on emphasizing the high salient double-layer IPM rotor structure in motor torque and efficiency improvement, that the deteriorated machine performances caused by reducing PM usage is compensated by employing higher saliency rotor structure. The higher rotor saliency effect, the lesser magnet material is necessary in IPM motor for maintaining the same machine performance [4]. Since the higher-saliency usually relates to more complex rotor structure design, the tradeoff of PM material cost reduction and manufacture difficulties must be considered.

The torque and efficiency performance of LSPMM are analyzed by using equivalent circuit method (ECM) coupled with finite element analysis (FEA) and verified by test. A general good agreement confirmed the present performance prediction.

II. Model and Analysis Method

A. Prototype Single-phase LSPMM

In this study, the prototype analysis model is built from a single-phase LSPMM used as air-condition compressor, as Fig. 1 shows. The main and auxiliary winding arranged in the stator slot regions are connected as the illustrated electric circuit. The starting capacitances (C_s), running capacitances (C_r) and positive temperature coefficient (PTC) are connected to auxiliary winding in parallel for increasing starting torque and power factor [5]. In the rotor part, the conductor bars and PM segments are buried in the iron core. TABLE I lists the main specification of the LSPMM model.

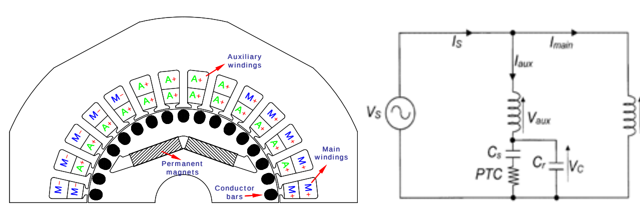


Fig. 1. Prototype LSPMM model and stator winding connection circuit

TABLE I
SPECIFICATION OF PROTOTYPE SINGLE-PHASE LSPMM MODEL

Item	Value	Unit
Pole / Slot number	2 / 28	
B_r [75 °C]	1.168	[T]
Magnet volume/pole	(4.7×19.0)×2	[mm^3]
Stack length	90	[mm]
Air gap length	0.5	[mm]
Input voltage	220	[Vrms]
Rate Speed	3000	[Rpm]
Rated torque	6.5	[Nm]

B. Performance Analysis in Single-phase LSPMM

In this magnet reduction study, the single-phase LSPMM is analyzed focusing on the maximum output torque capability and motor efficiency performance at steady operation, "T_max." and "η" in short, respectively.

Since the unbalanced stator magnetic field from main and auxiliary windings can be converted into a two-phase frame of balanced *d*-*q* plane, the unbalanced field is dealt with symmetrical coordinate method [6]. Therefore, a well accepted equivalent circuit method (ECM) is introduced for quickly predicting the LSPMM performances. Fig. 2 shows the equivalent circuits in *d*-*q* plane, that composing of *d*-axis/*q*-axis positive sequence circuit and negative sequence circuit respectively.

In addition, to carry out the equivalent circuits, the precious machine parameters are necessary, such as Back-EMF, *d*-*q* axis inductances, which varying with currents and phase angles, and equivalent resistance of iron loss. Therefore, 2-dimensional FEA is used to calculate the required parameters.

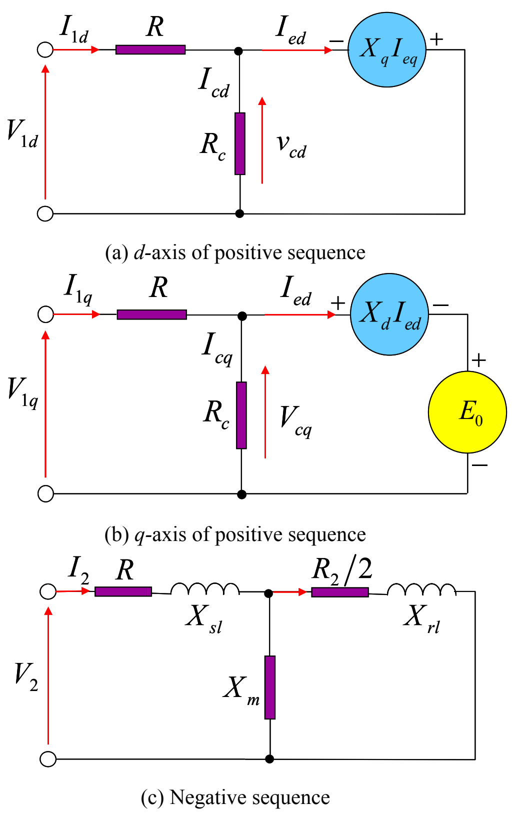


Fig. 2. Steady state equivalent circuits of single-phase LSPMM

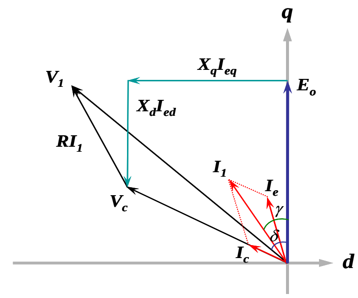


Fig. 3. Vector diagram of single-phase LSPMM in *d*-*q* plane

The steady state performances of LSPMM are similar to IPMSM, that hybrid synchronous torque is generated at synchronous operation. According to the *d*-*q* axis equivalent circuits and the vector diagram illustrated in Fig. 3, as well as the stator electric circuit, the voltage and current equations, and output power, torque production, motor efficiency performance calculation are given as followings [6], [7]:

$$\begin{cases} I_{1d} = I_{ed} + I_{cd} \\ I_{1q} = I_{ed} + I_{cq} \end{cases} \quad [1]$$

$$\begin{cases} V_{1d} = RI_{1d} - X_q I_{eq} \\ V_{1q} = RI_{1q} + X_d I_{ed} + E_o \end{cases} \quad [2]$$

$$\begin{cases} \mathrm{I}_{aux} = \dfrac{1}{\sqrt{2}}\left[\mathrm{I}_1\left(1 + j\dfrac{\cot\varepsilon}{\beta}\right) + \mathrm{I}_2\left(1 - j\dfrac{\cot\varepsilon}{\beta}\right)\right] \\ \mathrm{I}_{main} = -\dfrac{1}{\sqrt{2}\beta}\csc\varepsilon\left[\mathrm{I}_1 - \mathrm{I}_2\right] \end{cases} \quad [3]$$

$$\begin{cases} P_{out} = P_1 + P_2 = \left(\mathrm{Re}(\mathrm{V}_1\mathrm{I}_1^*) - R\mathrm{I}_1^2\right) - \left(\mathrm{Re}(\mathrm{V}_2\mathrm{I}_2^*) - R\mathrm{I}_2^2\right) \\ \eta_{eff} = \dfrac{\mathrm{V_S}\cdot\mathrm{I_S}}{P_{out}} \times 100\% \end{cases} \quad [4]$$

$$\begin{cases} T = T_{Ps} + T_{Ns} = P_1/\omega_s + P_2/\omega_s \\ {}^*T_{Ps} = \left(T_M + T_R\right) = p\left(E_o I_{1q} + (L_d - L_q) I_{1d} I_{1q}\right) \end{cases} \quad [5]$$

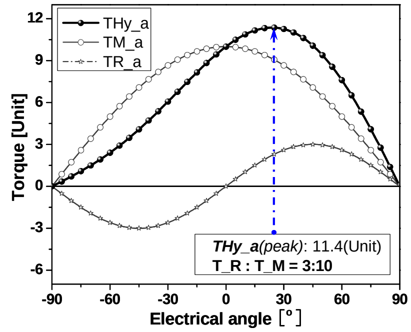
where, I_e is effective current in the positive sequence circuit, I_c is current consumed in iron loss, R_a is equivalent phase winding resistance, R_c is equivalent iron loss resistance, β is effective turn ratio between the main/auxiliary windings, ε is electrical angle between *d*-*q* axis, E_o is no-load Back-EMF.

III. DOUBLE-LAYER ROTOR DESIGN TECHNIQUE FOR REDUCING MAGNET USAGE

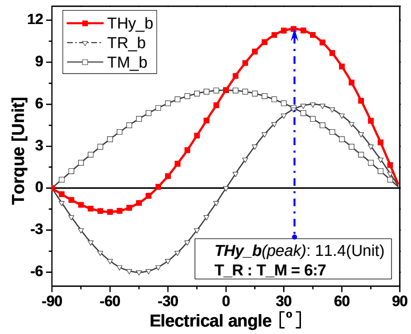
The LSPMM can utilize hybrid torque at synchronous operation, as the above torque equation presented. By adopting high salient double-layer IPM rotor structure, the reluctance torque is improved to compensate magnet torque, which helps to lower the dependency on magnet usage.

A. Hybrid Torque Characteristic Analysis

The hybrid torque production is considered as reluctance torque adding to magnet torque spatially [2]. Therefore the same maximum hybrid torque (T_{Hy}) is possible to be generated with different balance ratio (γ) of reluctance torque (T_R) to magnet torque (T_M), as Fig. 8 (a), (b) show γ_a=(3:10) and γ_b=(6:7). The higher balance ratio suggests higher rotor saliency, defined in term of *d*-*q* axis inductance, as (L_q/L_d).



(a) Identical hybrid torque $T_{\_peak}$ with low ratio of (T_R/T_M)



(b) Identical hybrid torque $T_{\_peak}$ with high ratio of (T_R/T_M)

Fig. 4. Hybrid torque characteristics according to different balance ratio

B. Torque-Efficiency Map Approach

By performing the given *d-q* axis equivalent circuits, the torque and efficiency performance of the prototype LSPMM is calculated firstly, that maximum output torque T_max.= 13.0[Nm] and efficiency at steady state η=90[%], both of which will be constrained in the magnet reduction design.

For easily observing both of the design constrains in design, torque and efficiency characteristics are mapped together. Fig. 5 shows an example of "torque-efficiency" map. With a constant saliency ratio γ=2.5, the T_max. and η of LSPMM model are predicted as functions of phase Back-EMF (E_o) and *d*-axis inductance *Ld.* It is easy to judge the tendency of torque and efficiency improvement, as the arrows illustrate. Then, the required constrains of T_max.= 13.0[Nm] and η=90[%] contour lines are expressed with bold. It is obvious that the crossing point "A" of the contour lines is the desired point, which satisfied both of T_max. and η constrains. In the LSPMM design, the corresponded machine parameters Back-EMF (E_o) and *d*-axis inductance *Ld* of "A" should be achieved.

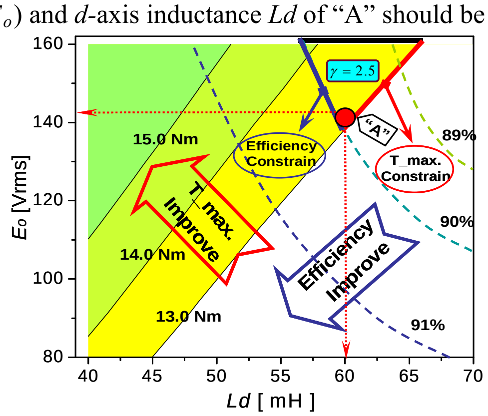


Fig. 5. Torque-Efficiency map of LSPMM with given γ=2.5.

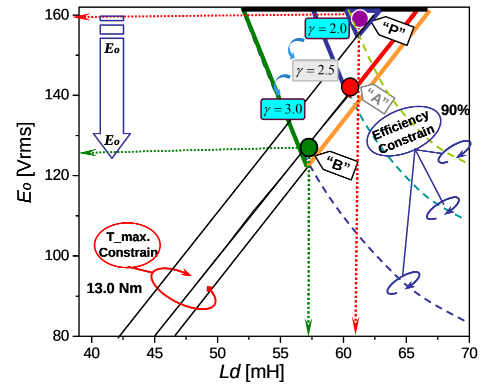


Fig. 6. Developed Torque-Efficiency map for estimating magnet reduction

With the same simulation approach, the torque-efficiency map is developed to map with different given saliency ratio γ [2.0, 2.5, 3.0], and only the contour lines of T_max.= 13.0[Nm] and η=90[%] are marked, which determined several desire point, prototype model "P" with γ=2.0, and estimated model "B" with γ=3.0, as Fig. 6 illustrates.

From the hybrid torque characteristic analysis, the higher rotor saliency helps to reduce PM usage. It is well confirmed by the developed torque-efficiency map, that the desired point with higher saliency ratio corresponds to lower Back-EMF value, which is used to generally estimate the reduction of magnet usage. From the design point "P" to point "B", the Back-EMF (E_o) dereased from 160[Vrms] to 123[Vrms]. It can be estimated that nearly 23[%] PM can be reduced if the assumed saliency ratio and correspond Back-EMF (E_o) and *d*-axis inductance *Ld* can be achieved in the LSPMM design.

C. Double-layer IPM Rotor Design Technique

RSM is a collection of statistical and mathematical techniques used for developing, improving and optimizing process [8]. It is applied to search a high salient double-layer IPM rotor structure in LSPMM for realizing PM reduction.

From the torque-efficiency map analysis, the rotor saliency ratio γ at steady operating condition (@3000rpm, I_m=8A, β=40°) and Back-EMF (E_o) are chosen as objective functions in the optimal design of double-layer LSPMM. Fig. 7 illustrates the basic model of double-layer IPM rotor structure with given design variables [*L_pm1, L_pm2* and α] and margin limitations for fully considering mechanical strength. By performing the RSM simulation, the responses of objective functions vary with three design variables among their experiment ranges, as Fig. 8 shows. The predicted objective values are well achieved (Back-EMF: 123[V], γ=3.0). Then, the optimized double-layer LSPMM model is built by using the corresponded values of design variables, as Fig. 9 shows.

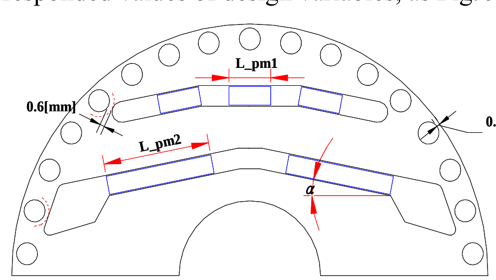


Fig. 7. Double-layer IPM rotor design model in RSM optimization.

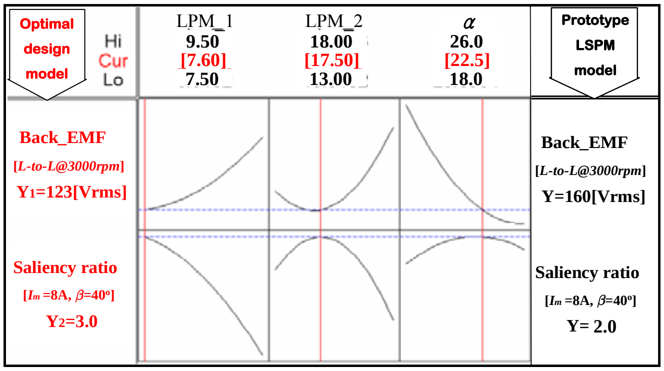


Fig. 8. Optimization analysis of Back-EMF and saliency ratio by RSM

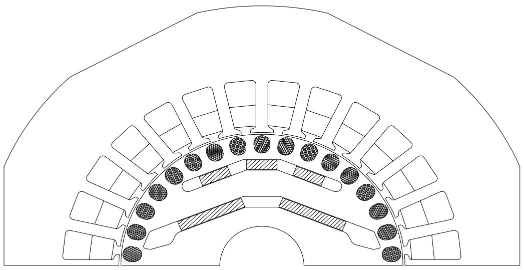


Fig. 9. Optimized double-layer design LSPMM model [with 75% PM]

IV. Result and Discuss

A. *Prototype LSPMM and Test*

The given constrain of torque performances in the magnet reduction design are confirmed by experiment method. The prototype single-layer LSPMM, with using 100% amount of PM is tested for confirming the maximum output torque capability calculated by presented ECM coupled with FEA. Fig. 10 shows the fabricated prototype LSPMM and its experiment setting.

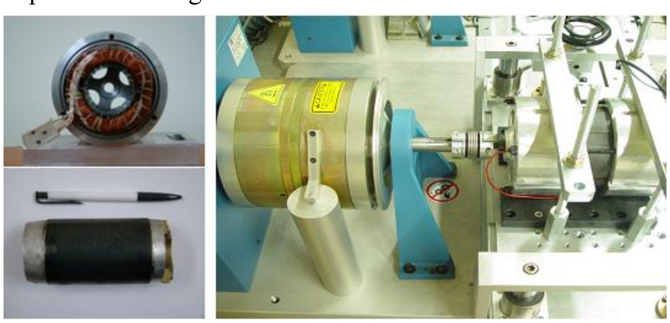


Fig. 10. Fabricated LSPMM and experiment setting

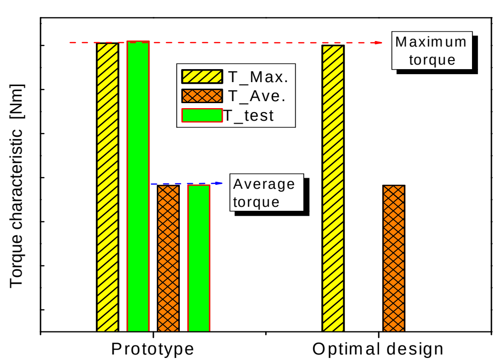


Fig. 11. Torque performance of single-phase LSPMM

TABLE II
Comparison Between Single-layer model and Double-layer Model

Model	Back-EMF @3000(rpm) L-to-L[V_{rms}]	Saliency ratio [I_m=8(A), β=40°]	Max. Torque [N*m]	Motor Efficiency [%]
Prototype [100%]PM	160.0	2.0	13.1	90.0
Optimal design [75%]PM	123.1	3.0	13.0	89.8

B. *LSPMM Characteristics Comparison*

According to the torque-efficiency map analysis, the optimized double-layer LSPMM has lower Back-EMF but higher rotor saliency characteristics, and achieves almost same torque and efficiency performances with saving 25% PM. TABLE II lists the concluded results, which well proved the estimated magnet reduction by torque-efficiency analysis. Also, the torque performance of single-layer LSPMM and double-layer LSPMM are tested and compared in Fig. 11.

V. Conclusion

This paper has presented a theoretical and experimental study of magnet reduction in a single-phase LSPMM by emphasizing double-layer IPM structure advantage without worsening main machine performances. By utilizing the "torque-efficiency map" approach, the magnet reduction is estimated according to rotor saliency improvement. The single-layer LSPMM was optimized into double-layer LSPMM design realized estimated magnet reduction. The test of LSPMM at steady state performance well validated the presented analysis approach. In general, the double-layer IPM rotor design help to reduce the dependency on magnet usage, but to improve rotor saliency with reduced magnet is quite different, and the manufacture cost will increase.

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