

Starting Torque Optimization of High-speed Switched Reluctance Motor Based on Level Set Method

Haijun Zhang^{1,2}, Weijie Xu¹, Shuhong Wang¹, Youpeng Huangfu¹, Guolin Wang¹
and Jianguo Zhu³

¹Faculty of Electrical Engineering Affiliation, Xi'an Jiaotong University, Xi'an, 710049, China

²Faculty of Hydroelectric Power, Hebei University of Engineering, Handan, 056038, China

³Faculty of Engineering and Information Technology, University of Technology, Sydney, NSW2007, Australia

E-mail: shwang@mail.xjtu.edu.cn

Abstract—For improving the starting torque performance in a two phases 4/2 high-speed switched reluctance motor, this paper proposes a novel rotor structure with soft magnetic material powders embed inner of the rotor poles. The torque dead zone and its key factors are analyzed through magnetic equivalent circuit approach. High permeability powders are used to adjust the equivalent reluctance in rotor poles, which can change the magnetic field distribution, produce the non-uniformity of flux paths and enhance the inductance ratio at aligned and unaligned positions. To achieve the desired static torque profile and low torque ripples, level set method is applied to optimize the rotor salient pole including multiple materials. In addition, results compared with the artificial density method indicate the advantages and effectiveness of the level set method in application of electrical machine design.

Index Terms—Switched Reluctance Motor; Torque ripple; Level Set Method; Soft magnetic material

I. INTRODUCTION

SWITCHED RELUCTANCE MOTOR is very suitable for high-speed operation thanks to its distinct advantages: simple and rugged structure, no permanent magnet and windings in rotor, high reliability and fault tolerance. Until now, there are mainly three kinds of High-speed SRM (HsSRM): 6/4, 6/2 and 4/2 poles in researches and industrial applications [1-4]. Especially for 4/2 SRM, the speed can be developed to tens of thousands of RPM and this motor has been investigated widely due to its rugged rotor and the simplest controller with lower cost. Unfortunately, due to their intrinsic and special structure, this kind of SRM has no self-starting capability in both directions at aligned position. Fig.1 (a) and (b) show a conventional two phases 4/2 HsSRM in a sectional view and its linear torque and inductance curve respectively. Another drawback of this motor is large torque ripple. For improving the starting performance and reducing the torque ripple, some approaches with novel rotor structure or multi-objective optimization have been investigated [1-2]. Most methods minimize the torque dead zone by enlarging the air-gap length or chamfering the rotor saliency edge. However, shaping the salient outline of rotor pole or enlarging air-gap length overlarge may affect the pole arc coefficient of rotor and decrease the mean torque.

Our study presents a novel rotor structure which does not need to change the salient pole rotor profile, but to optimize its inner topology structure. Here, an effective topology and shape optimization approach, Level set based method is presented to improve static torque characteristics and reduce

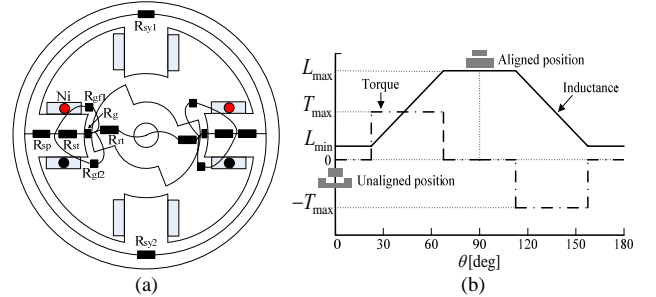


Fig. 1. (a) Sectional view of SRM. (b) Linear curve of torque to inductance. torque ripple. Element material properties in design domain can evolve automatically driven by level set function, which keep the salient outline of rotor as original shape. Meanwhile, the Higher Permeability Soft Magnetic Material (HPSMM) filled in optimized rotor salient poles can guide the variation of flux distribution at aligned position and enhance the magnetic flux density, obtaining a higher inductance ratio and mean torque. Electromagnetic field computation using finite element method and topology optimization using level set method is realized by combing with ANSYS software and FORTRAN program.

II. TORQUE ANALYSIS

This part is aiming to clarify the optimal design variable. Seen from the linear torque and inductance, as illustrated in Fig.1 (b), there is a wide torque dead zone at aligned position, which results in the lacking of self-starting capability. Main factors influencing torque characteristics are analyzed: the inductance value is constant at 0 degrees (unaligned position) and 90 degrees (aligned position), so there is no output torque in these regions, as expressed in (1).

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad (1)$$

The magnetic equivalent circuit (MEC) model in Fig.1 (a) indicates the equivalent electromagnetic parameters used for calculating the inductance. Here, the equivalent reluctance R_g and R_{r1} are considered as adjustable value for obtaining the varying inductance. The computation inductance L can be showed by (2).

$$L = N^2 \left(\frac{1}{R_{gt}} + \frac{1}{R_{gf}} \right) = N^2 \left(\frac{1}{R_{st} + R_g + R_{r1}} + \frac{1}{R_{gf}} \right) \quad (2)$$

where N is the number of winding turns; R_f is equivalent reluctance of $R_{gf1} // R_{gf2}$; $R_g = l_g / (\mu_0 A_g)$, $R_{r1} = l_{r1} / (\mu_r A_{r1})$. Then, the computation inductance is finally expressed as

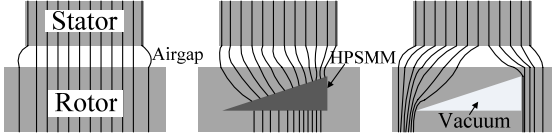


Fig. 2. Flux distribution and paths with different material properties.

$$L(l_g, \mu_r) = \frac{k_1}{k_2 + k_3 l_g + \frac{k_4}{\mu_r}} + k_5 \quad (3)$$

where $k_1 \sim k_5$ are assumed as constant coefficient. Here, only two variables l_g and μ_r are needed to be adjusted for making inductance varies at aligned and unaligned position. l_g is usually taken as a shape design variable [2]. The latter one can be considered as a design variable regarding to magnetic material properties, as used in Artificial Density Method [3].

III. ROTOR OPTIMIZATION AND RESULTS

A. Strategy for Improved Rotor Pole

In this paper, the HPSMM (such as higher Si% content) made up of powders is employed to lead the permeance vary. Fig.2 shows different flux distributions and flux paths varying with different magnetic material properties. In left, with uniform ferromagnetic materials, flux distributions and flux paths are nearly uniformity and symmetrical. In middle, with HPSMM in rotor salient poles, non-uniformity flux distributions and asymmetric paths are produced. There is a similar conclusion for the last figure, filled with vacuum or non-magnetic material.

B. Level Set Topology Optimization

The level-set based topology optimization is widely and successfully used for the structural topology and magnetic actuators thanks to its usefulness for the expression of evolving geometries [4]. In this paper, this method is applied to optimize the rotor structure of HsSRM for achieving the target static torque at any rotor position. The optimal objective function is expressed as following:

$$\begin{aligned} \text{Minimize } F(\mathbf{A}, \phi) &= \sum_{j=1}^n \lambda_j (T_{st} - T_{\text{target}})_j^2 H(\phi_j) \\ \text{Subject to } V(\phi) &\leq V_{\max}, \quad \sum_{j=1}^n \lambda_j = 1 \end{aligned} \quad (4)$$

where T_{target} and T_{st} are desired torque and static torque in the j th rotor position respectively; V_{\max} is the maximal volume in design domain; $H(\phi_j)$ is Heaviside function. Each iteration level set value can be solved though Hamilton-Jacobi equation.

$$\frac{\partial \phi(x, t)}{\partial t} + \mathbf{V}_n \cdot |\nabla \phi| = 0 \quad (5)$$

where \mathbf{V}_n is the normal velocity, which can be derived by sensitivity analysis equal to the derivative.

$$\mathbf{V}_n = -\frac{dF(\mathbf{A}, \phi)}{d\mathbf{v}} \quad (6)$$

where \mathbf{v} is design variable of reluctivity interpolated by:

$$\mathbf{v}_{i+1}^e = \left[\sum_{i=1}^3 (H(\phi_i(x, t))) / 3 \right]^p \cdot \mathbf{v}_i^e \quad (7)$$

where p is penalization power; \mathbf{v}_i^e is the element reluctivity.

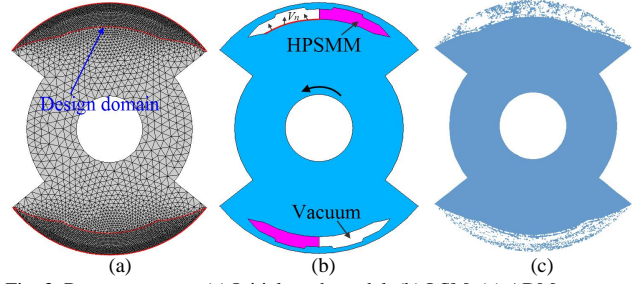


Fig. 3. Rotor geometry. (a) Initial mesh model. (b) LSM. (c) ADM.

C. Results and Analysis

Fig.3 shows rotor geometry in initial model with meshed elements, optimization model using Level Set Method (LSM) and Artificial Density Method (ADM). Compared with the LSM model, rotor in ADM model cannot be manufactured and used effectively. For a simpler and manufacturing more easily, the HPSMM region in (b) can be replaced by the ferromagnetic materials uniform as other part.

Fig.4 shows the magnetic flux density distribution. After level set optimization, the amplitude and distribution have been improved effectively. Fig.5 shows the torque profile in initial and optimal model with LSM. It can be seen that there is no dead torque zone after optimization, the mean torque is enhanced and torque ripple is also reduced largely.

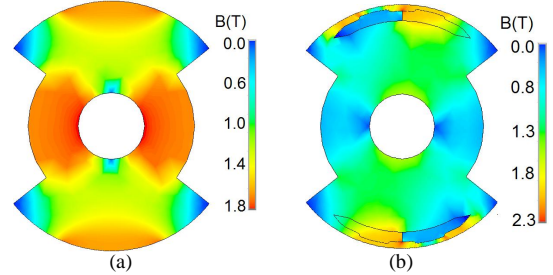


Fig. 4. Magnetic flux density. (a) Initial model. (b) LSM model.

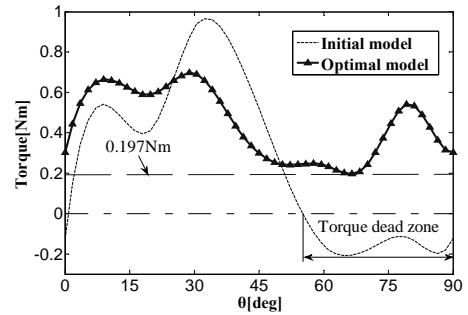


Fig. 5. Torque profile in initial and optimal model with LSM.

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