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Optimization Design of a Novel Synchronous Reluctance Motor with frequency domain finite element method

Zheng LI, LongFei XIAO, Chao BI

Key Lab of Modern Optical System, and Engineering Research Center of Optical Instrument and System of Ministry of Education, School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai, China

Abstract—**In the paper, the rotor shape described with Fourier series is presented in the synchronous reluctance motor. Using the Fourier series, Taguchi optimization method can combine with frequency domain finite element method (FEM) to explore the optimal rotor shape for achieving torque ripple reduction. This method can reduce significantly the number of parameters for optimizing and simplify the optimization procedure. In the optimization, frequency domain FEM is used to calculate the sample design and verify the proposed design from Taguchi analysis. 5-pole pairs VR resolver are used as example to show the optimization procedure and results.**

Index Terms - frequency domain, finite element method, Taguchi optimization method, synchronous reluctance motor.

I. INTRODUCTION

The synchronous reluctance motor (SynRel) provides a feasible rotor structural without the copper losses and cost-effective, comparable power density to induction motor [1-2].

II. THE MATH MODE OF THE SYNCHRONOUS RELUCTANCE MOTOR

The phase windings are concentrated to be installed on the slot in the stator.

The turns of phase windings in the ith teeth of the stator, N_{A_i} , $N_{\mathrm{B\_i}}$, N_{C_i} are

$$\begin{cases} N_{\mathrm{A\_i}} = N_{\max}\sin[(i-1)\dfrac{2\pi p}{Z}+0] \\ N_{\mathrm{B\_i}} = N_{\max}\sin[(i-1)\dfrac{2\pi p}{Z}+\dfrac{2\pi}{3}] \\ N_{\mathrm{C\_i}} = N_{\max}\sin[(i-1)\dfrac{2\pi p}{Z}-\dfrac{2\pi}{3}] \end{cases} \tag{1}$$

where $N_{\max}$ is the max turns of the signal coil, Z is the total teeth of the stator, p is the pole pairs of the stator windings.

Corresponding the one salient pole of the rotor about the synchronous reluctance motor, the air-gap δ can be expressed by Fourier series.

$$\delta = \delta_0 + \sum_{i=1}^{\infty}\delta_i\cos(ip\theta+\varphi_i) \tag{2}$$

where θ is the position mechanical angle at the one salient pole of rotor, p is the salient pole pairs of rotor, φ_i is the angle of phase, δ_i is coefficient of Fourier series.

Corresponding the one salient pole of the rotor, the air-gap permeance Λ can be presented by

$$\Lambda = \Lambda_0 + \sum_{i=1}^{\infty}\Lambda_i\cos(ip\theta+\varphi_i) \tag{3}$$

The phase current i_a, i_b, i_c can be presented by

$$\begin{cases} i_a = I_m\sin(2\pi ft+\theta) \\ i_b = I_m\sin(2\pi ft+\dfrac{2\pi}{3}+\theta) \\ i_c = I_m\sin(2\pi ft-\dfrac{2\pi}{3}+\theta) \end{cases} \tag{4}$$

The stator winding three-phase voltages and currents can be expressed on the rotor dq-axies as

$$\begin{cases} u_{sd}=R_s i_{sd}+\dfrac{d\psi_{sd}}{dt}-\omega_r\psi_{sq} \\ u_{sq}=R_s i_{sq}+\dfrac{d\psi_{sq}}{dt}+\omega_r\psi_{sd} \end{cases} \tag{5}$$

where u_{sd} , u_{sq} , i_{sd} , i_{sq} , ψ_{sd} , ψ_{sq} is the stator voltage , current and flux linkages components projected onto the rotor dq axes, respectively. R_s is the stator winding phase resistance. ω_r is the rotor angular speed.

The flux linkages ψ_{sd}, ψ_{sq} can be generally expressed as

$$\begin{cases} \psi_{sd}=L_{sd}(i_{sd},i_{sq})\cdot i_{sd} \\ \psi_{sq}=L_{sq}(i_{sd},i_{sq})\cdot i_{sq} \end{cases} \tag{6}$$

The electromagnetic torque T_e can be generally expressed as

$$T_e = \frac{3}{2}p(\psi_{sd}i_{sq}-\psi_{sq}i_{sd}) = \frac{3}{2}p(L_{sd}-L_{sq})i_{sd}i_{sq} \tag{7}$$

III. FREQUENCY DOMAIN FINITE ELEMENT METHOD

Time-varying electromagnetic quantities have the periodic waveform in the VR resolver.

$$F(t) = F_m\cos(2\pi ft+\theta) \tag{8}$$

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All quantities have the same frequency f , but can have different phase angles θ .

The finite element method to compute the magnetic vector potential A and the electric scalar potential ϕ .

$$\nabla \times \frac{1}{\mu}(\nabla \times A) = (\sigma + j\omega\varepsilon)(-j\omega A - \nabla\phi) \qquad (9)$$

$$E = -j\omega A - \nabla\phi \qquad (10)$$

$$I_{total} = \int_{\Omega}(\sigma + j\omega\varepsilon)(-j\omega A - \nabla\phi)d\Omega \qquad (11)$$

$$T_e = \frac{dW_c(\theta,\mathrm{i})}{d\theta} = \frac{d}{d\theta}\int_V (\int_0^H B\cdot dH)dV \qquad (12)$$

where E is the electric field, μ is the magnetic permeability, ω is the angular frequency, σ is the conductivity, ε is the permittivity, I_{total} is the total current flowing in conductors. $W_c(\theta,\mathrm{i})$ is the magnetic coenergy of the motor.

IV. TAGUCHI OPTIMIZATION METHOD

Taguchi optimization method is effective for the reduction of FEM calculation number in the motor optimization process.

Design of Experiments (DOE) methodology for determining parameter levels. The $L_9(3^4)$ series of orthogonal arrays to model the design factors. The L_9 design is as follows:

TABLE I
ORTHOGONAL ARRAYS $L_9(3^4)$

run	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

coefficient δ_i of Fourier series of the air-gap in formula (2) is chose as A, B, C, and D.

The performances of the synchronous reluctance motor, the ripple of torque waveform, T_{ripple} can be calculated as follows:

$$T_{ripple} = \frac{T_{e\max} - T_{e\min}}{T_{avg}} \qquad (13)$$

where $T_{e\max}$ is the maximum electromagnetic torque? $T_{e\min}$ is the minimum electromagnetic torque. T_{avg} is the average electromagnetic torque.

V. EXPERIMENT ANALYSIS

Figure1 is the synchronous reluctance motor of the 5-Pole Pairs rotor.

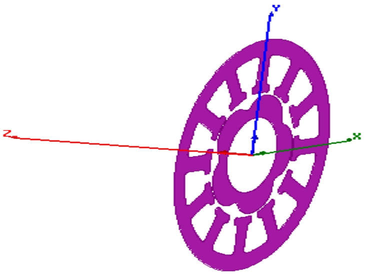

Fig. 1 Main structure of 5-Pole Pairs rotor of VR resolver.

Fig.2 shows the induced voltage of the winding of the synchronous reluctance motor. The slots of the stator are 12. The phase winding is installed in each teeth of the stator and its turns are different according to formula (1).

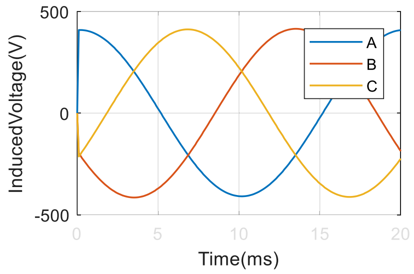

Fig. 2 the induced voltage of the winding.

The object function of the optimization is built by formula (13). T_{ripple} the ripple of torque is shown in Fig.3, and the T_{ripple} reaches 0.126%.

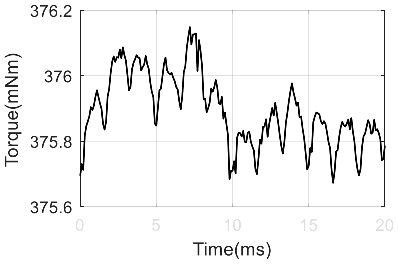

Fig. 3 the torque of the synchronous reluctance motor.

Experiment results show the optimization procedure is effective and believable.

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