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Frequency Domain Finite-element Analysis of Variable Reluctance Resolver

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Abstract—**The rotor shape of variable reluctance (VR) resolver is complicated, and this leads the optimization of the resolver be difficult. In the paper, a model for describe the air-gap with Fourier series is presented. This model can reduce significantly the number of parameters for optimizing and simplify the optimization procedure. Using the Fourier series, Taguchi optimization method can combine with frequency domain finite element method (FEM) to explore the optimal rotor shape for achieving the minimum total harmonic distortion THD of the induced voltage in the signal windings. 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, variable reluctance (VR) resolve.

I. INTRODUCTION

With the outstanding reliability and durability of the VR resolver, it is often applied as the angular sensor for electric vehicle (EV)motor. In the environments of vibration, high temperature and high-speed in EV, the VR resolver have a unique advantage [1-4].

II. THE MATH MODE OF THE VR RESOLVER

The signal and the excitation winding are concentrated to be installed on the slot in the stator.

The excitation winding has the same turn coils N .

$$N_{exc} = \pm N \tag{1}$$

where N_{exc} is the turns of the excitation coil, $\pm$ is the direction of the coil.

The turns of sin signal windings $N_{\sin\_i}$ and the turns of cos signal windings $N_{\cos\_i}$ in the ith teeth of the stator are

$$\begin{cases} N_{\sin\_i} = N_{\max} \sin[(i-1)\dfrac{2\pi P}{Z} + \alpha] \\ N_{\cos\_i} = N_{\max} \cos[(i-1)\dfrac{2\pi P}{Z} + \alpha] \end{cases} \tag{2}$$

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 signal windings, α is the angle between the first teeth and the axis of the winding.

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

$$\delta = \delta_0 + \sum_{i=1}^{\infty} \delta_i \cos(ip\theta + \varphi_i) \tag{3}$$

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

$$\Lambda = \Lambda_0 + \sum_{i=1}^{\infty} \Lambda_i \cos(ip\theta + \varphi_i) \tag{4}$$

The exciting current i_{exc} can be presented by

$$i_{exc} = I_m \sin(2\pi f_{exc} t) \tag{5}$$

The induced voltage of sin signal windings $E_{\sin}$ and cos signal windings $E_{\cos}$ are

$$\begin{cases} E_{\sin} = \sum_{i=1}^{\infty} E_{\sin\_i} \cos(2\pi f_{exc} t) \sin(ip\theta + \varphi_i) \\ E_{\cos} = \sum_{i=1}^{\infty} E_{\cos\_i} \cos(2\pi f_{exc} t) \cos(ip\theta + \varphi_i) \end{cases} \tag{6}$$

where f_{exc} is the frequency of the excitation winding.

III. FREQUENCY DOMAIN FINITE ELEMENT METHOD

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

$$F(t) = F_m \cos(2\pi f t + \theta) \tag{7}$$

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 .

$$\nabla \times \frac{1}{\mu} (\nabla \times A) = (\sigma + j\omega\varepsilon)(-j\omega A - \nabla\phi) \tag{8}$$

$$E = -j\omega A - \nabla\phi \tag{9}$$

$$I_{total} = \int_{\Omega} (\sigma + j\omega\varepsilon)(-j\omega A - \nabla\phi) d\Omega \tag{10}$$

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.

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 (3) is chose as A, B, C, and D.

The performances of the induced voltage of sin signal windings and cos signal windings, THD can be calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{\sum_{i=2}^{\infty} E_i^2}}{E_1} \qquad (11)$$

where E_i is the coefficient ith harmonic of the induced voltage in the signal windings.

V. EXPERIMENT ANALYSIS

Figure1 is the VR resolver of the 5-Pole Pairs rotor. The slots of the stator are 12. The excitation winding is installed in each teeth of the stator and its turns is same, but the direction of coil current is alternate. The concentrated signal windings are installed in some teeth according to formula (2).

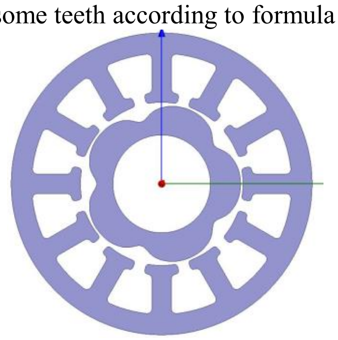

Fig. 1 Main structure of 5-Pole Pairs rotor of VR resolver.

Fig.2 shows the wave of induced voltage of the sin winding.

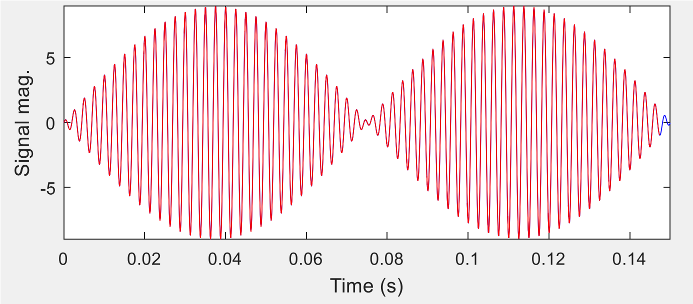

Fig. 2 the induced voltage of the sin winding.

The object function of the optimization is built by formula (11). THD of the induced voltage of the sin winding is shown in Fig.3, and the THD reaches 0.01%.

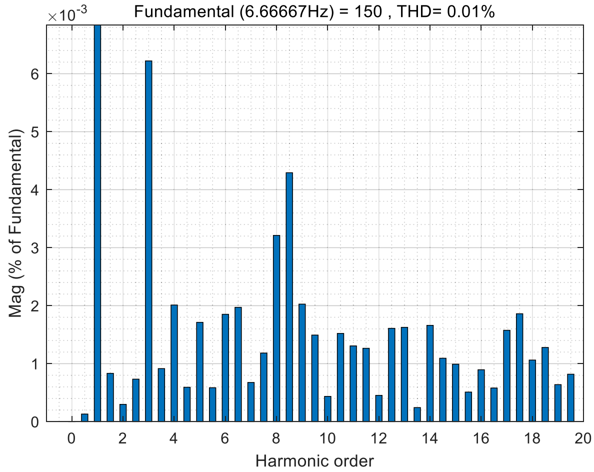

Fig. 3 THD of the induced voltage of the sin winding.

Experiment results show the optimization procedure is effective and believable.

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