Analysis of Fault-Tolerance Control Strategy of the Single Winding Bearingless PM Slice Motor

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Abstract: There always exists a problem towards multi-phase concentrated winding bearingless slice motor that the fault of the windings would lead to the motors' abnormal running when the control strategy is not changed. Taking the six-phases single winding bearingless slice motor for example. Firstly, the short-circuit current of the fault winding was analyzed while each of the winding worked at short-circuit fault state and the expression of the short-circuit current was derived based on the voltage balance equation of the fault winding. Secondly, every possible fault state in this motor was analyzed, and the corresponding fault-tolerance control strategy was presented based on the stator-current reconfiguration principle. In the strategy, the stator-current mathematical model was derived based on the mathematical model of motor's levitation force and torque. Finally, the fault-tolerance control strategy was verified by comparing levitation force's pulse and torque's pulse in the simulation.

Keywords: Bearingless, Slice Motor, Single-Winding Short-Circuit, Fault-Tolerance Control

Introduction

In the past 20 years, a novel bearingless slice motor which combined the rotation and suspension functions appeared, along with the development of the modern power switching devices, digital signal processors, sensors and modern control technology. Because of the advantages of no wear, unlubricated, no mechanical noise, simple structure and high reliability, this motor was applied widely in biochemistry, medical, semiconductor manufacturing and other fields with high requirements for purity[1-4]. At present, most of these motors use double winding structure both at home and abroad. However, this structure affects the reliability of the motors, therefore the practical application of it is limited.

So as to solve the problem mentioned above, a new structure that produced the rotation and suspension magnetic field by a single winding was proposed in paper[5]. Motors with this structure had good ability of fault-tolerance. Paper[6] concluded every possible open-circuit fault modes of bearingless slice motor and established corresponding fault-tolerance control strategy. However, the fault modes of short-circuit or occurring short-circuit and open-circuit simultaneously were not mentioned. So more comprehensive analysis of the fault-tolerance control technique was necessary.

In this paper, a more general fault-tolerance control strategy was established, and the corresponding stator-current mathematical model was put forward and verified by simulation.

Analysis of Short-circuit Current of the Windings

Fig.1 shows the basic structure of single winding bearingless slice motor. The air gap magnetic field was changed by controlling the stator-current according to radial levitation force and torque. But when one or more of the windings occured short-circuit fault, the stator-current of the fault windings wouldn't be controllable. So in order to analyze fault-tolerance control strategy, short-circuit current of the windings was analyzed according to the short-circuit winding's voltage balance equation in this paper.

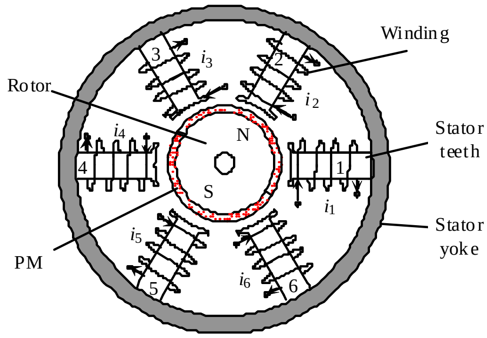

Fig. 1 Basic structure of single winding bearingless slice motor

The formula of air gap magnetic flux density is[5]:

$$B_g=\begin{cases}[W_1 i_n + a_{\mathrm{PM}}\cos(\theta-\theta_{\mathrm{r}}) - \frac{1}{6}\sum_{n=1}^{6} i_n W_1]\frac{\mu_0}{l_{\mathrm{eg}}}, & -\frac{\alpha}{2}+\frac{2\pi(n-1)}{6}\le\theta\le\frac{\alpha}{2}+\frac{2\pi(n-1)}{6}\\ 0, \quad \frac{\alpha}{2}+\frac{2\pi(n-1)}{6}\le\theta \text{ or } \theta\le-\frac{\alpha}{2}+\frac{2\pi(n-1)}{6} & \end{cases} \tag{1}$$

where $n = 1,2,\cdots,6$; μ_0 is air permeability; l_{eg} is length of air gap; θ is mechanic angle; α is width of stator teeth; W_1 is turn of coil; i_n is current of wingding n; a_{PM} is amplitude of magnetic potential; θ_{r} is the angle between pole N and stator teeth 1.

The voltage balance equation of the short-circuit winding is:

$$\frac{\partial \Psi_{\mathrm{M}}}{\partial\theta_{\mathrm{r}}}\omega+\frac{\partial \Psi_{\mathrm{L}}}{\partial i}\frac{\partial i}{\partial\theta_{\mathrm{r}}}\omega+iR=0 \tag{2}$$

Where i is short-circuit current; Ψ_{L} and Ψ_{M} are flux linkages produced by the short-circuit winding and other; ω is the speed of the rotor; R is resistance of coil.

Ψ_{M} and Ψ_{L} can be calculated by following equations:

$$\Psi_{\mathrm{M}}=W_1\int_{-\frac{\alpha}{2}+\frac{2\pi(n-1)}{6}}^{\frac{\alpha}{2}+\frac{2\pi(n-1)}{6}}[a_{\mathrm{PM}}\cos(\theta-\theta_r)-\frac{1}{6}\sum_{m=1,m\neq n}^{6}W_1 i_m]\cdot rh(\mu_0/l_{\mathrm{eg}})\mathrm{d}\theta \tag{3}$$

$$\Psi_{\mathrm{L}}=W_1\int_{-\frac{\alpha}{2}+\frac{2\pi(n-1)}{6}}^{\frac{\alpha}{2}+\frac{2\pi(n-1)}{6}}\frac{5}{6}iW_1 rh\frac{\mu_0}{l_{\mathrm{eg}}}\mathrm{d}\theta \tag{4}$$

Where h is permanent magnet thickness; r is radius of permanent magnet.

The ratio of Ψ_I and Ψ_{PM} is:

$$\Psi_I/\Psi_{\mathrm{PM}}\le\frac{1}{12}\alpha W_1\sum_{m=1,m\neq n}^{6}I_m/(a_{\mathrm{PM}}\sin\frac{\alpha}{2}) \tag{5}$$

Where Ψ_I and Ψ_{PM} are flux linkages produced by other normal windings and permanent magnet; I_m is amplitude of the current of stator teeth m.

From equation (5), it can be found that Ψ_I are much less than Ψ_{PM}. Therefore, in order to simplify the equation, Ψ_{PM} is used to estimate Ψ_M, and it can be calculated that the short-circuit current of winding n is:

$$i = p_1\cos(\theta_r - \frac{2\pi(n-1)}{6}) + p_2\sin(\theta_r - \frac{2\pi(n-1)}{6}) + p_3\{I_0 - p_1\cos[\theta_0 - \frac{2\pi(n-1)}{6}] - p_2\sin[\theta_0 - \frac{2\pi(n-1)}{6}]\} \quad (6)$$

Where θ_0 is initial angle of the rotor; I_0 is current before fault occuring; p_1、p_2、p_3 are expressions about parameters of the motor.

Classification of Fault Modes and Fault-tolerance Control Strategy

Classification of Fault Modes. Fault modes of the motor can generally be grouped to two kinds: open-circuit and short-circuit fault modes. Based on the number of the fault windings, fault modes of the six-phases single winding bearingless slice motor can be divided into one winding fault mode, two windings fault mode…six windings fault mode. According to the fact that when the number of the fault windings is more than two, the motor won't work normally. So the fault modes of the six-phases single winding bearingless slice motor are grouped into five: open-circuit of one winding, short-circuit of one winding, open-circuit of one windings, short-circuit of two windings, open-circuit of one winding and short-circuit of one winding simultaneously.

As the situation that one winding and open-circuit of two windings fault modes of the motor had been researched by some writers, this paper mainly analyzed short-circuit of two windings, open-circuit of one winding and short-circuit of one winding simultaneously fault modes of the motor.

Fault-tolerance Control Strategy. The formula of the radial levitation force and torque are[5]:

$$\begin{cases} F_x = \frac{k}{2}[(2i_1 - i_2 - i_3 + 2i_4 - i_5 - i_6)\cos\theta_r + \sqrt{3}(i_2 - i_3 + i_5 - i_6)\sin\theta_r] \\ F_y = \frac{k}{2}[\sqrt{3}(i_2 - i_3 + i_5 - i_6)\cos\theta_r + (-2i_1 + i_2 + i_3 - 2i_4 + i_5 + i_6)\sin\theta_r] \end{cases} \quad (7)$$

$$T = \frac{t}{2}[\sqrt{3}(i_2 + i_3 - i_5 - i_6)\cos\theta_r + (-2i_1 - i_2 + i_3 + 2i_4 + i_5 - i_6)\sin\theta_r] \quad (8)$$

Where F_x and F_y are radial levitation force along direction x and y; T is torque; k and t are coefficients about parameters of the motor.

The matrix form of formula (7) and (8) is:

$$\boldsymbol{Q} = \boldsymbol{M}\boldsymbol{i}_s \quad (9)$$

Where $\boldsymbol{Q} = [F_x, F_y, T]^T$; $\boldsymbol{i}_s$ refers to current of the windings; $\boldsymbol{M}$ is a matrix related to angle of the rotor.

The motor's steady operation is realized by controlling current of the windings. When levitation force and torque are given, the current of the windings can be calculated by formula (9) and some other additional conditions. From paper[6], it can be found that the expression of current in the constraints of least power is:

$$\boldsymbol{i}_\mathrm{s} = \boldsymbol{k}_\mathrm{m}(\theta_\mathrm{r})\boldsymbol{Q} \tag{10}$$

$$\boldsymbol{k}_\mathrm{m}(\theta_\mathrm{r}) = \boldsymbol{R}^{-1}\boldsymbol{M}^\mathrm{T}(\boldsymbol{M}\boldsymbol{R}^{-1}\boldsymbol{M}^\mathrm{T})^{-1} \tag{11}$$

When some of the windings occur fault, formula (9) also must be changed, or the current calculated by it won't meet the levitation force and torque needed by the motor.

If the windings occur open-circuit fault, the fault windings won't produce levitation force and torque. So the current of the fault windings i_k in formula (9) must be set to 0, where $k\in\{1,2,\cdots,6\}$; that is set row k of the matrix $\boldsymbol{M}$ to zero. And by this change, the new stator-current calculated by formula (10) and (11) will meet the levitation force and torque needed by the motor and make it maintain steady operation in open-circuit fault modes.

If the windings occur short-circuit fault, the current of the fault windings will be related to the speed of the rotor and other parameters and can't be controlled. Because the short-circuit current produces levitation force and torque too, the current of other normal windings must be reconfigured to meet the required levitation force and torque.

From formula (9) it can be calculated that the contribution of the short-circuit current to levitation force and torque is $\boldsymbol{M}(\boldsymbol{I}-\boldsymbol{\Lambda}_{6\times6})\,\boldsymbol{i}_\mathrm{s}$. Where $\boldsymbol{I}$ is a unit matrix; $\boldsymbol{\Lambda}_{6\times6}$ is a diagonal matrix, the elements of the diagonal are 1 or 0 when the corresponding windings are at normal or short-circuit fault mode.

Then the controllable levitation force and torque produced by the current of normal windings are:

$$\boldsymbol{Q}' = \boldsymbol{Q} - \boldsymbol{M}(\boldsymbol{I}-\boldsymbol{\Lambda}_{6\times6})\,\boldsymbol{i}_\mathrm{s} \tag{12}$$

Where the levitation force and torque in matrix $\boldsymbol{Q}$ are produced by all the windings including short-circuit fault windings.

So when some of the windings are at short-circuit fault mode, the mathematical model of the current of the other normal winding is:

$$\boldsymbol{i}_\mathrm{s} = \boldsymbol{k}_\mathrm{m}(\theta_\mathrm{r})\,\boldsymbol{Q}' \tag{13}$$

$$\boldsymbol{k}_\mathrm{m}(\theta_\mathrm{r}) = \boldsymbol{R}^{-1}\ \boldsymbol{M}'^\mathrm{T}(\boldsymbol{M}'\boldsymbol{R}^{-1}\ \boldsymbol{M}'^\mathrm{T})^{-1} \tag{14}$$

Where $\boldsymbol{M}' = \boldsymbol{M}\,\boldsymbol{\Lambda}_{6\times6}$.

From the above analysis, the open-circuit and short-circuit fault modes can be combined together. It can be concluded that when any of the windings is at fault mode, by changing the expressions of matrix $\boldsymbol{Q}$ and $\boldsymbol{M}$ according to the kinds of the fault modes, the mathematical model of the current of the normal winding can be derived as follow:

$$\boldsymbol{M}' = \boldsymbol{M}\,\boldsymbol{\Lambda}'_{6\times6} \tag{15}$$

Where $\boldsymbol{\Lambda}'_{6\times6}$ is a diagonal matrix. The elements of the diagonal are 1 or 0 when the corresponding windings are at normal or fault mode. Taking winding 1 at short-circuit fault and winding 4 at open-circuit fault simultaneously for example. At present, the first element of the diagonal in matrix $\boldsymbol{\Lambda}_{6\times6}$ should be set to 0, and both the first and the fourth elements of the diagonal in matrix $\boldsymbol{\Lambda}'_{6\times6}$ should be set to 0.

Simulation Analysis

From the analysis above, it can be found that by reconfiguring the current of other normal windings at fault modes, the levitation force and torque can be controlled effectively. In this section the fault modes of open-circuit of one winding and short-circuit of one winding simultaneously, and short-circuit of two windings will be researched. And the fault-tolerance control strategy of the fault modes will be verified by simulation.

Fault Mode of Open-circuit of One Winding and Short-circuit of One Winding Simultaneously. Taking winding 1 at short-circuit fault and winding 4 at open-circuit fault simultaneously for example. The expected levitation force and torque at the fault mode are: F_x=5N, F_y=5N, T=0.1N·m.

Fig.2(a) shows the levitation force and torque if the control strategy is not changed at the fault mode. At this time both the levitation force and torque have much pulse, and the motor can't work normally. Fig.2(b) shows the levitation force and torque if taking the fault-tolerant control strategy, it can be found that both the levitation force and torque have little pulse. The simulation results proved that the fault-tolerance control strategy was correct.

Fault Mode of Short-circuit of Two Windings. Taking both winding 1 and winding 2 at short-circuit fault for example. The levitation force and torque at fault mode of short-circuit of two windings are analyzed by simulation, and the expected values are the same as before. Fig.3(a) and fig.3(b) also show the levitation force and torque when following the control strategy at normal mode and taking the fault-tolerant control strategy. From the comparision, it can be found that the levitation force has the similar pulse of about 10% in the fault-tolerant control strategy, and can meet the motor's steady operation.

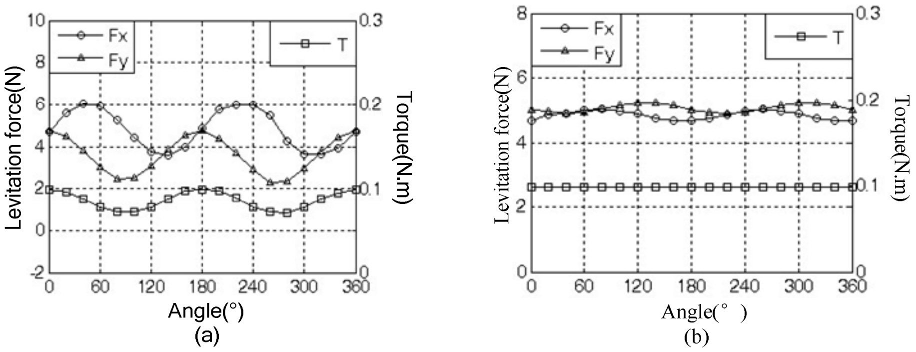

Fig. 2 Levitation force, torque of one winding at short-circuit fault and another phase at open-circuit fault mode

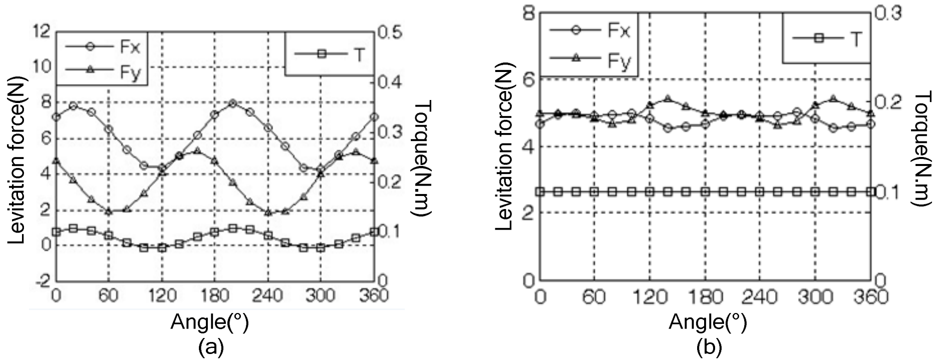

Fig. 3 Levitation force, torque of two phases at short-circuit fault mode

From the results of the simulation, it can be found that when some of the windings at fault, the fault-tolerant operation at fault mode of the motor can be achieved by changing the control strategy and reconfiguring the stator-current of the windings.

Summary

In this paper, the fault modes of the single winding bearingless slice motor were analyzed, and the expression of the short-circuit current was derived according to the short-circuit winding's voltage balance equation. Due to the characteristic that each winding of the motor can be controlled independently, a more general fault-tolerant control strategy was put forward and verified by simulation. This control strategy could be used at both one winding fault mode and two windings fault mode.

References

[1] Pascal Nang Bösch. Lagerlose Scheibenläufermotoren höherer leistung. Swiss Federal Institute of Technology Zurich. Zurich, Swiss, 2004.
[2] Amrhein W, Silber S, Nenninger K, et al. Developments on bearinglessdrive technology. The 8th Symposium Magnetic Bearings. Mito, Japan, 2002.
[3] Liao Qixin. Research on the bearingless PM slice motor. Nanjing University of Aeronautics & Astronautics. Nanjing, 2003.
[4] Xu Longxiang, Zhu Xiaochun, Yao Kai. Research on bearingless slice PM motor. Proceedings of the CSEE, 2006,26(6):141-145.
[5] Zhu Jun, Liao Qixin, Deng Zhiquan, et al. Control principle and realization of a type of error tolerant bearingless slice motor. Power Electronics, 2008(3):33-37.
[6] Yue Shengzou, Wang Xiaolin, Deng Zhiquan, et al. Operation characteristics analysis of the single winding bearingless PM slice motor at lacking-phase. Proceedings of the CSEE, 2009,29(23):80-86.