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Fault tolerant control with torque limitation based on fault mode for ten-phase permanent magnet synchronous motor

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Torque limitation

Abstract This paper proposes a novel fault tolerant control with torque limitation based on the fault mode for the ten-phase permanent magnet synchronous motor (PMSM) under various open-circuit and short-circuit fault conditions, which includes the optimal torque control and the torque limitation control based on the fault mode. The optimal torque control is adopted to guarantee the ripple-free electromagnetic torque operation for the ten-phase motor system under the post-fault condition. Furthermore, we systematically analyze the load capacity of the ten-phase motor system under different fault modes. And a torque limitation control approach based on the fault mode is proposed, which was not available earlier. This approach is able to ensure the safety operation of the faulted motor system in long operating time without causing the overheat fault. The simulation result confirms that the proposed fault tolerant control for the ten-phase motor system is able to guarantee the ripple-free electromagnetic torque and the safety operation in long operating time under the normal and fault conditions.

1. Introduction

Due to the distinct advantage of replacing the centralized hydraulic system and eliminating all its associated disadvantage, the more electric/all electric aircraft has been the development trend in the last decade.[1–3] The electrically powered actuation technology, as the key technology of the more electric/all electric aircraft, is widely applied to the flight control surface actuation system and fuel pump system, which plays an important role in flight safety. And extensive research work has been reported for the electrically powered actuator, which can be divided into two categories: electro-hydrostatic actuator (EHA)[4,5] and electro-mechanical actuator (EMA).[6–8] Electrical machine system is the crucial part of the electrically powered actuator and it has a critical influence on the servo-actuation system performance. As a result, as the aircraft is moving towards the developing direction with safer and

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higher reliability, it is considered important to further study the fault tolerant electrical machine system.

The multiphase permanent magnet synchronous motor (PMSM) has the advantage of high power density, high efficiency, and high fault tolerance, which is more and more applied to aerospace servo-actuation system.[9–11] However, under the motor phase windings' fault conditions, the unbalanced current will cause torque fluctuation even leading to a serious damage for the motor system. Therefore, the fault tolerant control of the multiphase PMSM is considered of importance. Extensive research work has been reported on the fault tolerant control of the multiphase PMSM under fault conditions. In Refs.[12–14], the optimal torque control is proposed to compute the remaining healthy phase current using the optimization algorithms for the multiphase PMSM under fault conditions. The current obtained in this approach contained higher order harmonics that cannot be selectively regulated. Refs.[15–17] proposed an optimal current control with the third harmonic current injection to reduce the torque fluctuation of the multiphase PMSM during the post-fault operation. The current obtained in this approach was not optimized to produce the electromagnetic torque with the minimum torque ripple. However, during the post-fault operation of the multiphase PMSM, the remaining health phase current will increase greatly, especially under the multiphase fault conditions, which will cause the system overheat fault in long operating time. And there is no literature about the fault tolerant control that can address this issue.

In this paper, we propose a novel fault tolerant control with the torque limitation based on the fault mode for the ten-phase PMSM under the open-circuit and short-circuit fault conditions, which is able to guarantee the ripple-free electromagnetic torque and the safety operation in long operating time during the post-fault operation. The main contributions of this paper are twofold. First, we propose an approach to systematically analyze the load capacity of the ten-phase PMSM system under different fault conditions. Second, a novel fault tolerant control with the torque limitation based on the fault mode is proposed to guarantee the ripple-free electromagnetic torque and the safety operation under the fault condition in long operating time. And this paper is organized as follows. The mathematical model of the ten-phase PMSM is developed in Section 2. Section 3 presents the fault tolerant control with torque limitation based on fault mode. And the simulation is conducted in Section 4. Finally, Section 5 concludes this paper.

2. Mathematical model

In this paper, the ten-phase PMSM with two stators (stator 1 and stator 2) and two rotors (rotor 1 and rotor 2) mounted on the same shaft is adopted, as shown in Figs. 1 and 2. Each set of the stator and the rotor can be considered as an 8-pole/10-slot five-phase PMSM with concentrated, single-layer and alternate teeth wound winding. And the short-circuit current can be limited to the rated current. Therefore, this motor has excellent fault tolerant capacity. The detailed ten-phase PMSM design is described in Ref.[18,19]. Note that the ten phase windings are A_1, B_1, C_1, D_1, E_1, A_2, B_2, C_2, D_2, E_2, and the subscript 1,2 represent the phase windings of the stator 1,2.

For the mathematical modeling, we assume that 1) the magnetic circuit of the ten-phase PMSM is linear, ignoring core

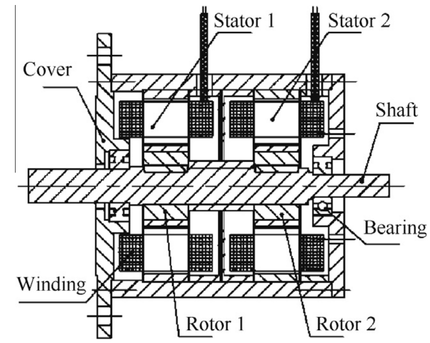

Fig. 1 The ten-phase PMSM.

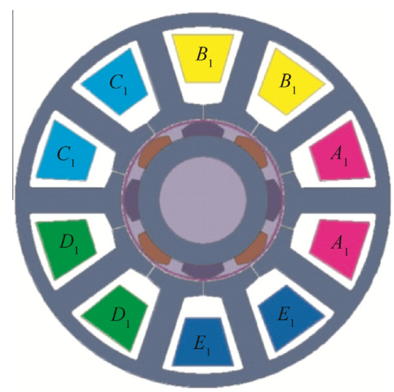

Fig. 2 Cross-section of stator 1 and rotor 1.

saturation, and 2) the back electromotive force (EMF) is sinusoidal. As a result, mathematical model of the ten-phase PMSM can be represented as

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega_r \tag{1}$$

$$\frac{\mathrm{d}\omega_\mathrm{r}}{\mathrm{d}t} = -\frac{B}{J}\omega_\mathrm{r} - \frac{T_\mathrm{L}}{J} + \frac{T_\mathrm{e}}{J} \tag{2}$$

$$T_\mathrm{e} = \sum_{i \in S} K_i I_i \tag{3}$$

$$K_i = K_m \sin(\omega_\mathrm{e} t + \theta_{\mathrm{e}i}) \tag{4}$$

where θ denotes the mechanical angle, ω_r the mechanical speed, B the damping coefficient, J the rotor moment of inertia, T_L the load torque, T_e the electromagnetic torque, S the set of phase windings, K_i the ith phase EMF coefficient, I_i the ith phase current; K_m denotes the peak phase EMF coefficient, which is equal to the ratio of the peak phase EMF to ω_r. Here ω_e is the electrical speed, and $\omega_\mathrm{e} = p\omega_\mathrm{r}$, where p is the pole pairs number. θ_{ei} is the initial phase electrical angle, which belongs to the following set:

$$\theta_{\mathrm{e}i} \in \left\{0, \frac{\pi}{10}, \frac{4\pi}{10}, \frac{5\pi}{10}, \frac{8\pi}{10}, \frac{9\pi}{10}, \frac{12\pi}{10}, \frac{13\pi}{10}, \frac{16\pi}{10}, \frac{17\pi}{10}\right\}$$

Under the phase fault conditions, the electromagnetic torque Eq. (3) of the ten-phase PMSM can be rewritten as

$$\begin{aligned} T_e &= \sum_{i \in S_\mathrm{n}} K_i I_i + \sum_{j \in S_\mathrm{f}} K_j I_j \\ &= T_\mathrm{u} + T_\mathrm{r} \end{aligned} \tag{5}$$