Chinese Journal of Aeronautics, (2015),28(2): 535–544

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

A novel fault tolerant permanent magnet synchronous motor with improved optimal torque control for aerospace application

Guo Hong, Xu Jinquan *, Kuang Xiaolin

School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China

Received 28 May 2014; revised 27 August 2014; accepted 3 November 2014
Available online 23 February 2015

KEYWORDS

Actuator;
Fault isolation;
Fault tolerant;
Optimal torque control;
Permanent magnet motor

Abstract Improving fault tolerant performance of permanent magnet synchronous motor has always been the central issue of the electrically supplied actuator for aerospace application. In this paper, a novel fault tolerant permanent magnet synchronous motor is proposed, which is characterized by two stators and two rotors on the same shaft with a circumferential displacement of mechanical angle of 4.5°. It helps to reduce the cogging torque. Each segment of the stator and the rotor can be considered as an 8-pole/10-slot five-phase permanent magnet synchronous motor with concentrated, single-layer and alternate teeth wound winding, which enhance the fault isolation capacity of the motor. Furthermore, the motor has high phase inductance to restrain the short-circuit current. In addition, an improved optimal torque control strategy is proposed to make the motor work well under the open-circuit fault and short-circuit fault conditions. Simulation and experiment results show that the proposed fault tolerant motor system has excellent fault tolerant capacity, which is able to operate continuously under the third open-circuit fault and second short-circuit fault condition without system performance degradation, which was not available earlier.

1. Introduction

With the development of power-by-wire (PBW) technology, the electrically supplied actuator has been the trend of servo-actuation system for aerospace application in the last decade,[1–3] due to the distinct advantage of replacing the centralized hydraulic system and eliminating all its associated disadvantages. In the past, the majority of the electrically supplied actuator can be divided into two categories: electro-hydrostatic actuator (EHA) and electro-mechanical actuator (EMA). There have been many successful applications, such as flight control surface actuators and fuel pumps[4] (for a survey, see, for example). Electrical machine system is the crucial part of the electrically supplied actuator, which determines the system performance of the servo-actuation system. Therefore, the electrical machine system with fault tolerant capacity has been the fundamental requirement in the aerospace application.

* Corresponding author. Tel.: +86 10 82339498.
E-mail address: xujinquan@buaa.edu.cn (J. Xu).
Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.01.008
1000-9361

Permanent magnet synchronous motor (PMSM) is widely used in servo-actuation system for aerospace application, due to the advantages of high power density and high efficiency.[5,6] However, the conventional three-phase PMSM has low armature magnetic field reconfiguration capacity and low fault isolation capacity, which cannot operate continuously under the fault condition. In order to meet the fault tolerant requirement of the PMSM in aerospace application, extensive research work has been reported on the fault tolerant PMSM (FTPMSM) design, which can be divided into two categories: the multiple sets of three-phase windings approach and the multiple single-phase windings approach.[4] For the multiple sets of three-phase windings approach, Bianchi et al.[7] proposed a dual three-phase PMSM, which is composed of two motors on the same shaft. Each motor is a three-phase PMSM. This FTPMSM can operate continuously with the first open-circuit fault. In Ref.[8], a FTPMSM with two sets of three-phase windings in the same stator is proposed. This FTPMSM cannot achieve the physical isolation between two sets of three-phase windings, and it is capable of continuous operation under the first open-circuit fault and short-circuit fault. In Ref.[9], a FTPMSM with four sets of three-phase windings is proposed, which consists of two motors on the same shaft. Each motor is a dual three-phase FTPMSM. This FTPMSM is able to operate continuously under the second open-circuit fault without system performance degradation. But this FTPMSM cannot operate continuously under the short-circuit fault, and it costs too much volume and weight, which is intolerable for the aerospace application. For the multiple single-phase windings approach, extensive research work has been reported on the four-phase, five-phase and six-phase FTPMSM with the fractional slot and concentrated windings[10–12] (for a survey, see, for example). This structure can improve the fault isolation capacity of the windings, and this FTPMSM is able to operate continuously under no more than the second open-circuit fault and short-circuit fault. However, in the practical engineering, this FTPMSM cannot guarantee the post-fault performance without system performance degradation under the fault condition. Since the current value of the remaining healthy phase windings for the FTPMSM under the fault condition will exceed the rated current value, the high current value will make the system overheat if the system still works without system degradation for long time. And the electromagnetic torque ripple will be larger under the second fault condition. Therefore, it is important to further explore the FTPMSM structure design to guarantee the post-fault performance without system performance degradation under the fault condition. Meanwhile, the control strategy for the FTPMSM is also one of the critical problems to be addressed urgently. Over the years, many important contributions have been made for the fault tolerant control of FTPMSM under the open-circuit fault and short-circuit fault, such as the optimal torque control in Refs.[13–15] and the optimal current control in Refs.[16–18] However, these fault control strategies cannot be applied for the FTPMSM with more than six-phase windings.

The scope of this paper falls into the FTPMSM system with the multiple single-phase windings approach. A novel FTPMSM, which can guarantee the post-fault performance under the third open-circuit fault and the second short-circuit fault without system performance degradation, is proposed in this paper.

2. FTPMSM design

PMSM is the crucial component of the electrically supplied actuator, which determines the system performance of the actuator. Therefore, it is vital to research the PMSM with high reliability. In this section, a novel FTPMSM is proposed as shown in Fig. 1. It is able to continually operate under the third open-circuit fault and the second short-circuit fault conditions. In addition, finite element analysis (FEA) of the electromagnetic field is adopted to analyze the characteristics of the proposed FTPMSM.

2.1. Structure design

In order to improve the fault tolerant capacity, the FTPMSM is characterized by two stators (stator 1 and stator 2) and two rotors (rotor 1 and rotor 2) on the same shaft with a circumferential displacement of 4.5° mechanical angle. 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, as shown in Fig. 2. Here A, B, C, D, E denote the five-phase windings in each segment of the FTPMSM, and the subscript 1 denotes that these five-phase windings are located in stator 1 (similarly, the subscript 2 denotes that these five-phase windings are located in stator 2). This structure is able to guarantee the physical separation, magnetic isolation and thermal isolation of the windings. Therefore, when some of the phase windings are under the fault condition, the normal phase windings can still work well. This enhances the fault isolation of the windings. Furthermore, the electrical isolation capacity of the motor can be achieved via the use of H-bridge power supply. In addition, the two segments of the stator and the rotor have a difference of 4.5° mechanical angle, which is used to reduce the cogging torque of the developed FTPMSM. Since the phase windings' structure is fixed, the unequal-thickness permanent magnet is utilized to improve the sinusoidal waveform of back electromotive force.

To make the FTPMSM work well under the short-circuit fault condition, a phase inductance design approach is proposed to restrict the short circuit current. Let E_δ denotes the back electromotive force of the FTPMSM, R the phase resistance, L the phase inductance, and ω the angular frequency. When $R << \omega L$, the short circuit current I_s can be represented as

$$I_s \approx \frac{E_\delta}{\omega L} \quad (1)$$

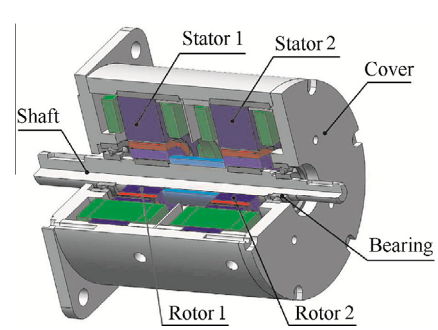

Fig. 1 Structure of the proposed FTPMSM.