Guaranteeing the Fault Transient Performance of Aerospace Multiphase Permanent Magnet Motor System: an Adaptive Robust Speed Control Approach

Jinquan Xu, Boyi Zhang, Hao Fang, and Hong Guo

***Abstract*—To enhance the fault transient performance of aerospace multiphase permanent magnet synchronous motor (PMSM) system, an adaptive robust speed control is proposed regardless of the phase open-circuit (OC) and short-circuit (SC) fault in this paper, which can be applied for both the redundant motor system and fault tolerant motor system. For aerospace multiphase PMSM system, besides external load disturbance and system parameter perturbation, there inevitably exists the electromagnetic torque ripple in fault transient process, which can degrade the system performance and even cause the system instability. To cope with this issue, the electromagnet torque ripple of the multiphase PMSM system in fault transient process is first analyzed. Then, by considering the electromagnet torque fluctuation caused by fault transient as a system uncertainty, a novel adaptive robust speed control scheme is proposed, while the adaptive law is constructed to emulate the total system uncertainty bound, which include the load disturbance, the parameter variation, and the electromagnetic torque fluctuation due to fault transient. The resulting control can ensure the speed control performance even in fault transient process regardless of the uncertainty, in which no prior estimation of the uncertainty bound is required. In addition, the proposed adaptive robust speed control is demonstrated by a six-phase PMSM experimental platform. The novelty of this research is to explore a novel adaptive robust speed control to strengthen the fault tolerance performance of multiphase PMSM system even in fault transient process, which requires no prior estimation of the uncertainty bound.**

***Index Terms*—Multiphase permanent magnet motor, fault transient, fault tolerance, adaptive robust control.**

I. INTRODUCTION

WITH the superiority of high fuel efficiency, good maintainability and low environmental noise, the more electric aircraft (MEA) has received much attentions in the modern commercial and military aerospace industries, such as Boeing B787, Airbus A380, and Lockheed F35 fighter [1]–[3].

The electrical machine system is one of the key components of the MEA, which is characterized by high power conversion efficiency and accurate torque control performance. Due to its outstanding technological advantage, the electrical machine system is being widely used for flight surface control, landing gear control and fuel pump, by replacing the conventional hydraulic actuation system. Therefore, the electrical machine system plays more and more important role in the overall aerospace applications [4]–[7].

To meet the reliability requirement of the MEA, considerable efforts have been conducted on the high reliability electrical machine system, such as switched reluctance motor (SRM), flux switching permanent magnet motor (FSPMM), and multiphase PMSM. Due to its simple rotor structure with no magnets or windings, the SRM has a good fault tolerance capacity, which can be applied for high-speed and high-temperature application [8]–[10]. But the SRM suffers from the relatively low power density, which is not suitable in aerospace application. To cope with this issue, by adding the permanent magnet in the stator, the FSPMM has the merits of high power density and good mechanical integrity, which has attracted much attention in the safety-critical applications [11]–[13]. In contrast to the FSPMM, the multiphase PMSM has the higher power density and efficiency, the lower torque ripple and electromagnetic noise, which make it very suitable for safety-critical aerospace applications.

Over the years, considerable efforts have been made on multiphase PMSM system, which can be classified into two categories: redundant motor system and fault tolerant motor system. The redundant motor system makes use of the multiple three-phase windings to improve the fault tolerant capacity, which has the more simple control structure and less power MOSFETs are required. The fault tolerant motor system utilizes multiple sets of single-phase winding to enhance fault tolerant capacity, which can provide more redundancy for fault tolerance. Over the past decade, many important contributions have been conducted. For example, in [14], [15], the dual and

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triple redundant PMSM system are proposed for the safety-critical application. In [16]–[19], the four-, five-, and six-phase fault tolerant PMSM (FTPMSM) system with different slot/pole combinations are proposed. Only by the appropriate control strategy, the fault tolerant PMSM system can guarantee the post-fault operation performance. In [20], [21], the optimal torque control (OTC) is proposed to enable the fault tolerant operation performance by minimizing the total copper loss. In [22], [23], the optimal current control is proposed to strengthen the post-fault performance by adding harmonic current in the remaining healthy phase. However, all these fault tolerant controls are focused on generating the steady output torque in post-fault operation, which can be activated only after the determination of the fault type. In practice, due to the existence of the fault diagnosis, there inevitably exists the fault transient process between fault appearance and fault tolerant control in effect, in which the torque fluctuation will be emerged for multiphase PMSM system [4], [24], [25]. This will deteriorate the control performance and stability of the system, which is not permitted in some critical aerospace applications (i.e. flight surface control system). At present stage, the fault tolerant control with guaranteed fault transient performance for multiphase PMSM system has not attracted much attentions and remains as a challenging issue.

The motivation of this research is to explore a novel control approach to enhance the fault tolerant performance (including fault transient performance) for multiphase PMSM system, which can be applied both for the redundant motor system and fault tolerant motor system. The salient contributions of this research are threefold. First, the electromagnetic torque ripple in fault transient process is thoroughly analyzed for multiphase PMSM system, including redundant motor system and fault tolerant motor system. Second, by taking the torque fluctuation in fault transient as a system uncertainty, this paper proposes a generalized robust control structure for multiphase PMSM system regardless of the uncertainty. Third, the adaptive law is proposed to emulate the total system uncertainty bound, which was not available earlier. The proposed control can ensure the speed control performance of multiphase PMSM system in presence of various uncertainties, while the fault transient performance can be also guaranteed.

II. THE MULTIPHASE PMSM SYSTEM

A. The Multiphase Motor

To enhance the fault tolerant capacity, the six-phase PMSM is proposed, as shown in Fig. 1(a), which has twelve stator slots and ten poles. To decrease the high harmonics in phase back electromotive force (EMF), the permanent magnets with eccentricity structure are adopted. In addition, the per-unit phase inductance is designed to restrict the phase SC current. Table I shows the design specification of the multiphase motor.

Fig. 1(b) shows the motor magnetic flux line distribution. There exists little coupled magnetic flux for the windings. This implies the good magnetic isolation performance for the proposed motor. Fig. 2 shows the back EMF waveform and the phase inductance of the proposed motor. The maximum SC current value is 2.45 A, which can solve the issue caused by the excessive SC current.

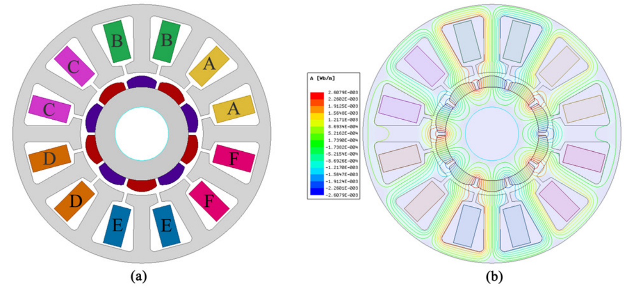


Fig. 1. The six-phase motor structure.

TABLE I
THE MOTOR DESIGN SPECIFICATION

Parameters[Unit]	Value
DC bus voltage [V]	42
Rated power [W]	50
Rated speed [rpm]	2400
Load torque [N·m]	0.2

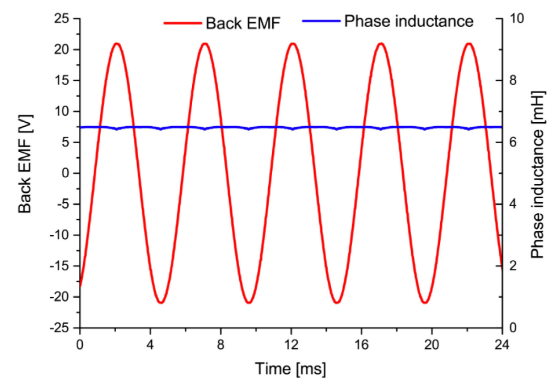


Fig. 2. The phase back EMF and inductance waveforms at 2400 rpm.

B. The Fault Tolerant Drive Configuration

The fault tolerant drive is the significant component of the multiphase motor system. Over the past decades, many important contributions have been conducted for the six-phase PMSM, which mainly can be classified as: six-phase fault tolerant PMSM system and dual redundant PMSM system.

The six-phase FTPMSM system utilizes the independent H-bridge power inverter to power each phase winding, as shown in Fig. 3(a). That is, twenty-four power switches are required.

As a result, this FTPMSM has the excellent fault isolation. Due to the multiple single-phase winding architecture, the six-phase FTPMSM system can ensure the continuous operation even in two faulted phase by the appropriate fault tolerant control strategy.

The dual redundant PMSM system adopts two sets of three-phase full bridge power inverter to power the two sets of three-phase windings, as shown in Fig. 3(b), which needs twelve power switches. This system can only achieve the post-fault continuous operation in one phase fault condition by the traditional vector control strategy, regardless of phase OC and SC faults.

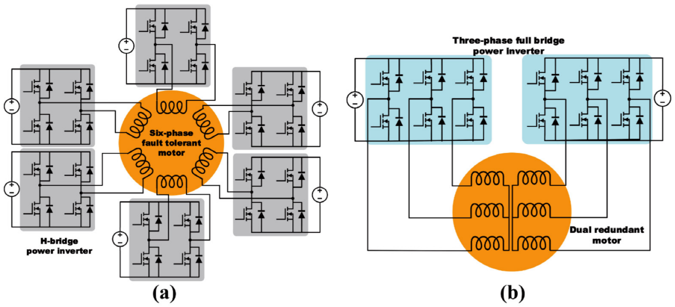


Fig. 3. The fault tolerant and dual redundant motor systems.

In contrast to the dual redundant PMSM system, although the more power switches are required, the six-phase FTPMSM system has the stronger fault tolerant capacity. Moreover, the FTPMSM system needs the more complex fault tolerant control strategy to ensure the control performance with fault than dual redundant PMSM system.

Note that for both the six-phase fault tolerant motor system and the dual redundant motor system, there inevitably exist the fault transient process between the fault occurrence and fault tolerant control in effect, which will result in the serious system performance degradation. To address this issue, this paper proposes a generalized adaptive robust speed control to enhance the system robustness, especially for the improvement of the fault transient performance.

III. Torque Ripple Analysis in Fault Transient

For the adaptive robust control design, the fault transient electromagnet torque fluctuation is thoroughly analyzed for both the six-phase FTPMSM system and the dual redundant PMSM system in this section.

To analyze the fault transient electromagnet torque fluctuation, the mathematical model of multiphase motor system is required, which consists of a mechanical subsystem and an electrical subsystem. The mechanical subsystem is the same for both the six-phase FTPMSM system and the dual redundant PMSM system, which can be written as

$$\frac{d\theta}{dt} = \omega , \quad (1)$$

$$\frac{d\omega}{dt} = -\frac{B}{J}\omega - \frac{T_L}{J} + \frac{T_e}{J} , \quad (2)$$

where θ, ω, B, J, T_L and T_e denote mechanical angular position, mechanical angular speed, damping coefficient, moment of inertia, load torque, and electromagnetic torque, respectively. The electrical subsystem is associated with the system drive configuration and the operation condition, which will be introduced in the following.

A. Six-phase FTPMSM System

The electrical subsystem of the six-phase FTPMSM system can be in the form o

$$T_e = \sum_{i \in S} K_i I_i , \quad (3)$$

with

$$K_i = K_m \sin[\theta_e + (i-1)\frac{\pi}{3}] , \quad (4)$$

where K_i denotes the i^{th} phase back EMF coefficient, I_i denotes the i^{th} phase current, S denotes the set of all phase windings, K_m denotes the maximum phase back EMF coefficient, and θ_e denotes the electrical angular position.

For the system with phase OC and SC faults, the subsystem (3) can be rewritten as

$$T_e = \sum_{i \in S_h} K_i I_i + \sum_{i \in S_f} K_j I_j , \quad (5)$$

where S_{h} and S_f denote the set of non-faulted and faulted windings, respectively. For the system in fault, the fault tolerant control is utilized to produce the steady electromagnetic torque by the remaining healthy phase winding. Fig. 4 shows the six-phase FTPMSM control scheme. In the past, considerable efforts have been conducted on the fault tolerant control, such as the OTC and the harmonic current injection based control method. Note that for the six-phase FTPMSM system, the fault tolerant control can take effect only after the fault mode is determined. That is, there inevitably exists the fault transient process between fault occurrence and fault tolerant control in operation. Next, the electromagnetic torque ripple of the FTPMSM system in fault transient process will be analyzed.

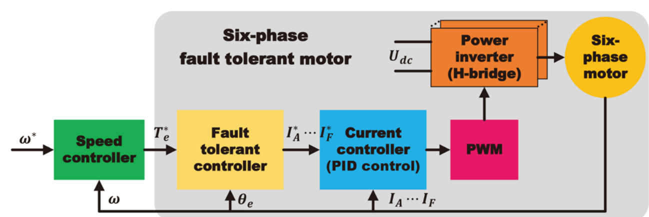


Fig. 4. The six-phase FTPMSM control scheme.

Let I_m denote the phase current maximum value. For phase OC fault transient process, since the faulted phase current is zero, by (4), the electrical subsystem (5) can be taken as

$$\begin{aligned} T_e &= \sum_{i \in S_h} K_i I_i = \sum_{i \in S} K_i I_i - \sum_{j \in S_f} K_j I_j \\ &= \sum_{i-1}^{6} K_m I_m \sin^2[\theta_e + (i-1)\frac{\pi}{3}] \\ &\quad - \sum_{i \in S_f} K_m I_m \sin^2[\theta_e + (j-1)\frac{\pi}{3}] \\ &= 3K_m I_m - \sum_{j \in S_f} K_m I_m \sin^2[\theta_e + (j-1)\frac{\pi}{3}] . \end{aligned} \quad (6)$$

For phase SC fault transient process, let I_S denote the maximum value of the faulted phase current. The electrical subsystem (5) can be rewritten as

$$\begin{aligned} T_e &= \sum_{i\in S_h} K_m I_m \sin^2[\theta_e + (i-1)\frac{\pi}{3}] \\ &\quad + \sum_{i\in S_f} K_m \sin[\theta_e + (j-1)\frac{\pi}{3}] I_S \sin[\frac{\pi}{2} - \theta_e - (j-1)\frac{\pi}{3}] \\ &= 3K_m I_m - \sum_{i\in S_f} K_m I_m \sin^2[\theta_e + (j-1)\frac{\pi}{3}] \\ &\quad + \sum_{i\in S_f} \frac{K_m I_S}{2} \sin 2[\theta_e + (j-1)\frac{\pi}{3}]. \end{aligned} \tag{7}$$

Therefore, for six-phase FTPMSM system with fault, by (6)-(7), the electrical subsystem can be represented as

$$T_e = T_{uf} + \Delta T_{ef}, \tag{8}$$

with

$$T_{uf} = 3K_m I_m, \tag{9}$$

where T_{uf} denotes the smooth electromagnetic torque part and ΔT_{ef} denotes the torque fluctuation part due to phase fault, which is associated with the fault type. Note that after the fault tolerant control in effect, the torque ripple part ΔT_{ef} can be eliminated by appropriately controlling the non-faulted phase.

B. Dual Redundant Motor System

For the dual redundant motor system, the dual three-phase windings simultaneously operate in normal condition, while only the non-faulted three-phase windings operate in fault condition. That is, each redundancy of the dual three-phase motor operates at half load in normal condition. In phase OC fault condition, the normal redundancy operates at full load, and the fault redundancy is disconnected. In phase SC fault, the normal redundancy operates at full load, while the faulted three-phase windings are short connected in the terminal to decrease the torque fluctuation due to the SC current. Fig. 5 shows the control scheme of the dual redundant motor system.

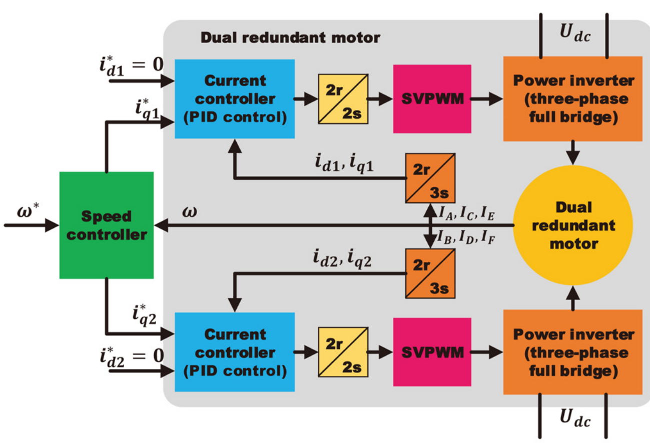


Fig. 5. The control scheme of dual redundant motor system.

Due to the generality of the electromagnetic torque expressions (3) and (5), the electromagnetic torque expressions (6) and (7) for fault tolerant motor system in fault transient process can also be applied for dual redundant motor system. Although the total electromagnetic torque in fault transient process is the same for both the fault tolerant and dual redundant motor systems, the electromagnetic torque ripple of the non-fault redundancy in fault transient process is different from the fault tolerant motor system. That is, in fault transient process, the electromagnetic torque generated by the non-fault redundancy is used for both driving the load and overcoming the torque fluctuation due to the faulted redundancy.

For phase OC fault transient process, by (6), the electrical subsystem of dual redundant motor system can be rewritten as

$$\begin{aligned} T_e &= \frac{3}{2}K_m I_m \underbrace{- \sum_{j\in S_f} K_j I_j \sum_{i\in S_f} K_m I_m \sin^2[\theta_e + (j-1)\frac{\pi}{3}]}_{\text{generated by fault redundancy}} \\ &\quad + \frac{3}{2}K_m I_m. \end{aligned} \tag{10}$$

Therefore, the torque ripple generated by the fault redundancy in fault transient process can be considered as a load disturbance of the non-fault redundancy. The electrical subsystem for the non-faulted redundancy can be expressed in the form of

$$T_e = T_{ur} + \Delta T_{er} \tag{11}$$

with

$$T_{ur} = \frac{3}{2}K_m I_m, \tag{12}$$

$$\Delta T_{er} = \sum_{i\in S_f} K_m I_m \sin^2[\theta_e + (j-1)\frac{\pi}{3}], \tag{13}$$

Similarly, for phase SC fault transient process, by (7), the electrical subsystem of the non-faulted redundancy can be represented in the form of (11) with

$$T_{ur} = \frac{3}{2}K_m I_m, \tag{14}$$

$$\begin{aligned} \Delta T_{er} &= \sum_{i\in S_f} K_m I_m \sin^2[\theta_e + (j-1)\frac{\pi}{3}] \\ &\quad - \sum_{i\in S_f} \frac{K_m I_S}{2} \sin 2[\theta_e + (j-1)\frac{\pi}{3}]. \end{aligned} \tag{15}$$

Note that after removing the fault redundancy, all load torque will be driven by the non-fault redundancy, that is, the smooth electromagnetic torque part T_{ur} of the non-fault redundancy will increase to $3K_m I_m$. Furthermore, by (8) and (11), for both the six-phase fault tolerant and dual redundant motor systems in fault transient process, the electromagnetic torque can be considered to be composed of the controlled electromagnetic torque part (T_{uf} or T_{ur}) and the uncontrolled electromagnetic torque part (ΔT_{ef} or ΔT_{er}), which will provide a guideline for the adaptive robust control design.

IV. Adaptive Robust Control Design

In practical engineering, besides the torque fluctuation due to the fault, there inevitably exist load disturbance and parameter variation for the six-phase motor system. The influence of the load disturbance and parameter variation can be considered as a load torque ripple. All these system uncertainties may degrade the system performance and even cause the system instability. To enhance the robustness and strengthen the fault transient performance, this paper proposes an adaptive robust speed control of the six-phase motor system (as shown in Fig. 4-5) by creatively considering the uncontrollable electromagnetic torque ripple as a system uncertainty. Furthermore, the adaptive law is presented for the system uncertainty bound estimation.

By (8) and (11), the mechanical subsystem (2) of the six-phase motor system can be rewritten as

$$\frac{d\omega}{dt}=-\frac{B}{J}\omega-\frac{T_L}{J}+\frac{1}{J}(T_u+\Delta T_e), \tag{16}$$

where T_u denotes the controllable electromagnetic torque, and ΔT_e denotes the uncontrollable electromagnetic torque caused by the fault. Define the speed error as

$$e_\omega=\omega-\omega_r, \tag{17}$$

where ω_r denotes the angular speed command signal. As a result, we have

$$\omega=e_\omega+\omega_r. \tag{18}$$

With (18) in (16), we have

$$\frac{de_\omega}{dt}=-\frac{B}{J}(e_\omega+\omega_r)-\frac{T_L}{J}+\frac{1}{J}(T_u+\Delta T_e). \tag{19}$$

Note that in practice, the system parameters B and J are both positive. Furthermore, the load torque disturbance T_L and the torque fluctuation ΔT_e caused by the fault are bounded, but the bound is unknown. Then the robust control is proposed as

$$T_u=-\frac{\alpha\hat{\rho}}{|\alpha|+\varepsilon} \tag{20}$$

with

$$\alpha=\frac{e_\omega}{J}\hat{\rho}, \tag{21}$$

and ε is a strictly positive constant, which will be designed based on the system performance requirement and the practical engineering experience. Here $\hat{\rho}$ is the estimation of the total system uncertainty, which is determined by the adaptive law as follows:

$$\dot{\hat{\rho}}=\kappa_1\left|\frac{e_\omega}{J}\right|-\kappa_2\hat{\rho}. \tag{22}$$

where $\hat{\rho}(t_0)>0$. Here $\kappa_1>0$ and $\kappa_2>0$ are the design parameters.

Note that the adaptive law (22) is of leakage type. Furthermore, $\hat{\rho}(t)>0$ for all $\hat{\rho}(t_0)>0$ and $t>t_0$. As a result, there is no singularity problem for the proposed adaptive robust control (20) and (22). Let

$$\rho=|B\omega_r|+|T_L|+|\Delta T_e|. \tag{23}$$

As a result, the adaptive law (22) can be considered as the estimation of ρ , which is associated with the upper bound of the total system uncertainty. Next, the system performance under the proposed control will be analyzed.

Theorem 1. For the system (19), the robust control (20) with the adaptive law (22) can guarantee the following performance:

(i) *Uniform boundedness:* For any $r>0$, there is a $d(r)<\infty$ such that if $\|\delta(t_0)\|\le r$,then $\|\delta(t)\|\le d(r)$ for all $t\ge t_0$.

(ii) *Uniform ultimate boundedness:* For any $r>0$ with $\|\delta(t_0)\|\le r$, there exists a $\underline{d}\ge 0$ such that $\|\delta(t)\|\le \bar{d}$ for any $\bar{d}\ge\underline{d}$ as $t\ge t_0+T(\bar{d},r)$, where $T(\bar{d},r)<\infty$.

Proof: Consider the Lyapunov function in the form of

$$V=\frac{1}{2}{e_\omega}^2+\frac{1}{2\kappa_1}(\hat{\rho}-\rho)^2. \tag{24}$$

Taking the time derivative of (24) yields

$$\dot{V}=e_\omega\dot{e}_\omega+\frac{1}{\kappa_1}(\hat{\rho}-\rho)\dot{\hat{\rho}}. \tag{25}$$

Substituting (19)-(21) into (25), we have

$$\begin{aligned}\dot{V}&=e_\omega-\frac{B}{J}(e_\omega+\omega_r)-\frac{T_L}{J}+\frac{1}{J}(T_u+\Delta T_e)\\&\quad+\frac{1}{\kappa_1}(\hat{\rho}-\rho)\dot{\hat{\rho}}\\&\le-\frac{B}{J}{e_\omega}^2+\left|\frac{e_\omega}{J}\right|(|B\omega_r|+|T_L|+|\Delta T_e|)\\&\quad+\frac{e_\omega}{J}T_u+\frac{1}{\kappa_1}(\hat{\rho}-\rho)\dot{\hat{\rho}}\\&\le-\frac{B}{J}{e_\omega}^2++\left|\frac{e_\omega}{J}\right|(|B\omega_r|+|T_L|+|\Delta T_e|)\\&\quad+\frac{\alpha^2-\varepsilon^2}{|\alpha|+\varepsilon}+\frac{1}{\kappa_1}(\hat{\rho}-\rho)\dot{\hat{\rho}}\\&=-\frac{B}{J}{e_\omega}^2++\left|\frac{e_\omega}{J}\right|(|B\omega_r|+|T_L|+|\Delta T_e|)\\&\quad-|\alpha|+\varepsilon+\frac{1}{\kappa_1}(\hat{\rho}-\rho)\dot{\hat{\rho}}.\end{aligned} \tag{26}$$

with (22) and (23) in (26), we have

$$\begin{aligned}\dot{V}&=-\frac{B}{J}{e_\omega}^2+\left|\frac{e_\omega}{J}\right|\rho-\left|\frac{e_\omega}{J}\right|\hat{\rho}+\varepsilon\\&\quad+\frac{1}{\kappa_1}(\hat{\rho}-\rho)\left[\kappa_1\left|\frac{e_\omega}{J}\right|-\kappa_2\hat{\rho}\right]\\&=-\frac{B}{J}{e_\omega}^2-\frac{\kappa_2}{\kappa_1}(\hat{\rho}-\rho)\hat{\rho}+\varepsilon\\&\le-\frac{B}{J}{e_\omega}^2-\frac{\kappa_2}{\kappa_1}(\hat{\rho}-\rho)^2+\frac{\kappa_2}{\kappa_1}|\hat{\rho}-\rho||\rho|+\varepsilon\\&\le\underbrace{-\frac{B}{J}{e_\omega}^2}_{\le 0}+\underbrace{\frac{\kappa_2|\rho|^2}{4\kappa_1}+\varepsilon}_{>0}.\end{aligned} \tag{27}$$

Therefore, by [26]–[28], the proposed control (20)-(22) can ensure the system performance (uniform boundedness and uniform ultimate boundedness) in the presence of various uncertainties, including the electromagnetic torque ripple due to the fault and the load torque ripple associated with the load disturbance and the parameter variation.

The essence of the proposed control is to utilize the robustness property of the adaptive robust control to guarantee the fault transient performance of the six-phase PMSM system by taking the electromagnetic torque ripple in fault transient process as a kind of the system uncertainty.

V. Experimental Result

To validate the effectiveness of the proposed control, the experimental platform of the six-phase PMSM system is built, as shown in Fig. 6, which consists of the six-phase PMSM, the DSP (TMS320F28335) and FPGA (EP2C35F484) based digital controller, fault tolerant power drive circuit, power source, host computer, and hysteresis dynamometer. The fault tolerant power drive circuit can be configured into two modes: the H-bridge based power drive mode and three-phase full bridge based power drive mode.

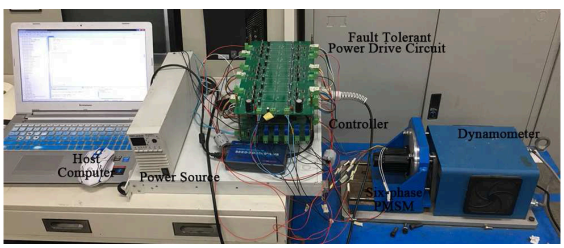


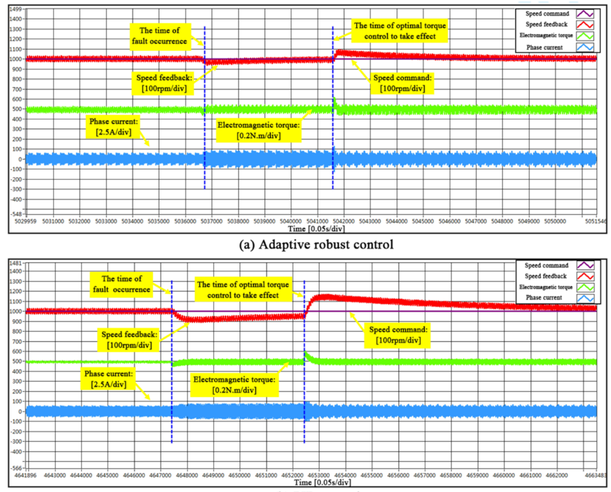
Fig. 6. The experimental platform of the six-phase PMSM system.

A. *Experiment of Six-phase FTPMSM System*

For six-phase FTPMSM system, the fault tolerant power drive circuit is constructed based on Fig. 3 (a) and 4, in which the OTC is used to make the FTPMSM output the steady electromagnetic torque in fault condition [29], [30]. Note that the fault transient time is set as 0.25*s* only for demonstration purpose, which is based on the fault diagnosis strategy in practice.

Fig. 7 shows the fault tolerant performance comparison under one phase OC fault with the proposed adaptive robust control and the proportion-integration-differentiation (PID) control, in which the PID parameters are designed by root locus approach and practical engineering experience. During the fault transient process, the maximum speed deviation for the adaptive robust control is 40*rpm* and the speed deviation can approach to zero in 0.05*s*, while the maximum speed deviation of the PID control is 110*rpm* and the speed deviation cannot be eliminated. Furthermore, when the OTC takes effect, the controlled system with the adaptive robust control has the smaller speed error and the shorter settling time than the PID control.

Fig. 8 shows the fault tolerant performance comparison under one phase SC fault for the proposed control and the PID control. After the phase SC fault occurrence, the adaptive robust control can the maximum speed deviation no more than

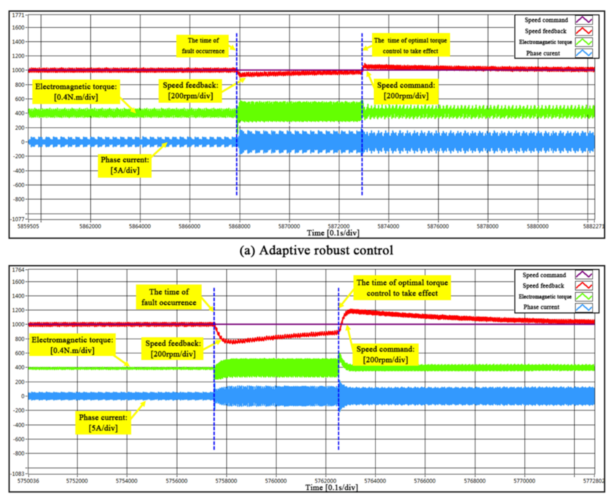


(a) Adaptive robust control

(b) PID control

Fig. 7. Fault tolerant performance comparison with OC fault.

100rpm, while the settling time is less than 0.2*s*. The maximum speed deviation of the PID control is 210*rpm*, and the corresponding settling time is more than 0.4*s*. Therefore, the adaptive robust control has the better fault transient performance than the PID control.



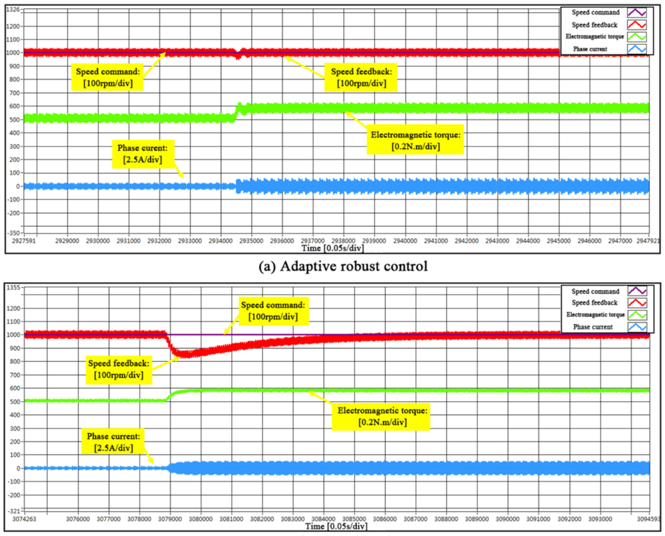
(a) Adaptive robust control

(b) PID control

Fig. 8. Fault tolerant performance comparison with SC fault.

Fig. 9 shows the performance comparison of the rated load torque step response for the proposed control and PID control. The adaptive robust control can guarantee the maximum speed deviation no more than 2% of the speed command, and the speed deviation can be eliminated rapidly (less than 0.03*s*). For the rated load torque step of the PID control, the maximum speed deviation is 180*rpm*, and the settling time is 0.25*s*, which is much longer than the adaptive robust control. Therefore, the FTPMSM system with the adaptive robust control has the better dynamic response performance.

Note that the proposed adaptive robust control can greatly strengthen the speed control performance of the six-phase FTPMSM system in the fault transient performance, while the maximum values of the current and the torque ripples are almost the same with that of the PID control.



(a) Adaptive robust control

(b) PID control

Fig. 9. Performance comparison with load torque step response.

B. Experiment of Dual Redundant Motor System

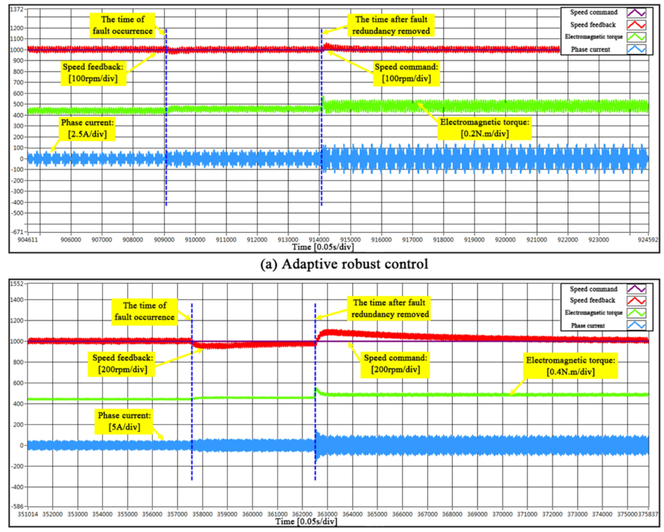
For dual redundant motor system, the power drive circuit is constructed based on Fig. 3(b) and Fig. 5. In phase OC fault, the faulted three phase windings are all removed. For phase SC fault, the faulted three phase windings are short connected in the terminal to eliminate the torque fluctuation associated with the SC current.

Fig. 10 shows the fault tolerant performance comparison under one phase OC fault. The maximum speed deviation of the adaptive robust control and the PID control are 50*rpm* and 100*rpm*, respectively. This means that the system with the adaptive robust control has the smaller speed fluctuation than the PID control. In addition, the adaptive robust control has the shorter settling time (0.025*s*) than the PID control (more than 0.15*s*).

Fig. 11 shows the fault tolerant performance comparison under one phase SC fault. The maximum speed deviations of the adaptive robust control is 100*rpm*, and the settling time is less than 0.05*s*. The maximum speed deviations of the PID control is 250*rpm*, and the settling time is more than 0.25*s*. Note that for both phase OC and SC faults, the adaptive robust control has the better speed control performance.

Fig. 12 shows the performance comparison with rated load torque step. The maximum speed deviation of the adaptive robust control is 50*rpm*, which is far smaller than the PID control (190*rpm*). Furthermore, the settling time of the adaptive robust control and the PID control are 0.05*s* and 0.55*s*, respectively. Therefore, the proposed control has the better dynamic performance.

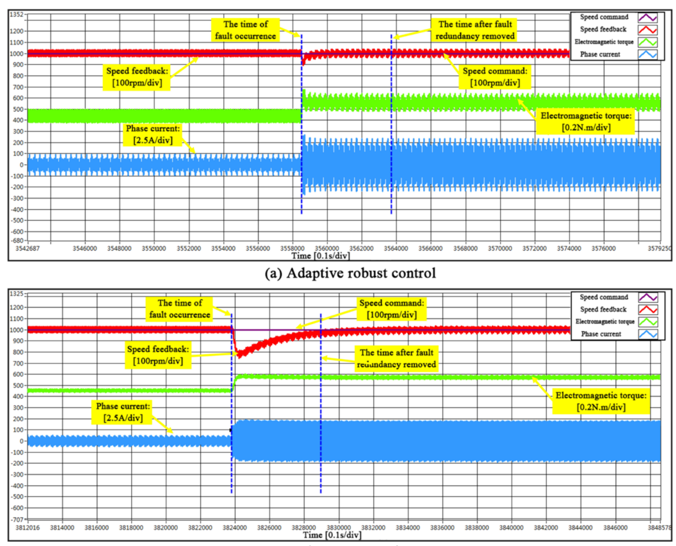
Note that the proposed adaptive robust control can greatly strengthen the speed control performance of the dual redundant motor system in the fault transient performance. However, due to the fast response performance of the electromagnetic torque, the proposed adaptive robust control has a little bigger current and the torque ripples than these of the PID control.



(a) Adaptive robust control

(b) PID control

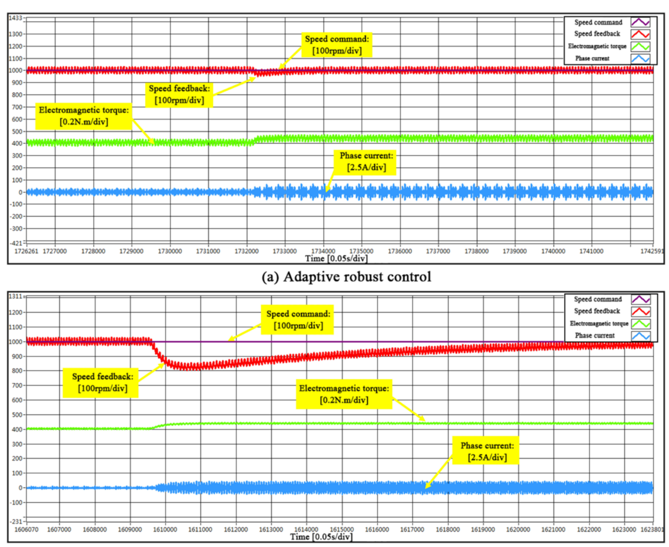
Fig. 10. Fault tolerant performance comparison with OC fault.



(a) Adaptive robust control

(b) PID control

Fig. 11. Fault tolerant performance comparison with SC fault.



(a) Adaptive robust control

(b) PID control

Fig. 12. Performance comparison with load torque step response.

VI. CONCLUSION

This paper proposes an adaptive robust speed control for the aerospace multiphase PMSM system with guaranteed fault transient performance. The electromagnetic torque ripples in fault transient process of the multiphase PMSM system are thoroughly analyzed. By taking the torque fluctuation in fault transient process as a system uncertainty, an generalized adaptive robust speed control scheme is proposed for the aerospace multiphase PMSM system, while the adaptive law is proposed for the uncertainty bound estimation, involving the load disturbance, the parameter variation, and torque fluctuation in fault transient process. The proposed control can ensure the speed control performance in the presence of various uncertainties, which can also ensure the fault transient performance of the multiphase PMSM system.

Compared with the traditional fault tolerant control, this paper proposes an active control approach (the adaptive robust control) to guarantee the fault transient performance of the multiphase PMSM system by innovatively taking the torque fluctuation into the control design. Since the fault transient performance is guaranteed, the longer fault diagnosis time is permitted for the practical multiphase PMSM system, which can effectively decrease the difficulty of the online fault diagnosis. Further explanation on the adaptive robust control to guarantee the fault transient performance by eliminating the torque ripple in post-fault operation is also interesting and worth pursuing.

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