ARTICLE IN PRESS

ISA Transactions xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Observer based fault tolerant control for a class of Two-PMSMs systems

Hongyun Xiong, Ye Liao, Xiaoyan Chu*, Xiaohong Nian, Haibo Wang

School of Information Science and Engineering, Central South University, Changsha, Hunan 410075, PR China

ARTICLE INFO

Keywords:
PMSM
FTC
Robust adaptive observer
Fault estimation
LMI

ABSTRACT

In this paper, an observer-based state-feedback fault-tolerant controller is proposed for two coupling permanent magnet synchronous motors (PMSMs) system. The controller compensates the actuator faults and allows the system states to track the reference states corresponding to the output of the original two-PMSMs system. To design such a controller, the information of system actuator faults are required. Then, a robust adaptive observer is designed to estimate the system actuator faults firstly. Next, by setting the reference outputs the equilibrium control inputs and reference speeds are computed based on the mathematic model of the two-PMSMs system. Meanwhile, the variation dynamic model is derived. Additionally, the robust stability of the closed-looped system with fault-tolerant controller is analyzed via the Lyapunov theory and interval matrix. Sufficient stability conditions and the gain matrix of the fault-tolerant controller are obtained by solving the linear matrix inequalities (LMIs). Finally, simulation results are presented to illustrate the effectiveness of the proposed observer and fault tolerant control (FTC) scheme.

1. Introduction

Coupling two-PMSMs systems, which are composed of two PMSMs, are widely used in the industry, agriculture, and transportation, etc. Different from the traditional single motor system, interaction usually exists between the two motors. In engineering practices, the two motors usually influence each other through springs, belts, gears, etc., such as web transport system, railway traction system and paper machine [1–3]. In real application, the main control objective of these systems is to obtain the desirable tracking and synchronization performance. Up to now, there is only a few researches about these systems. Based on the results of [4–8], the authors of [9] firstly establish the dynamic mathematical model of two coupling PMSMs system with nonlinear uncertain constrains. Simultaneously, various controllers are designed based on the established two coupling PMSMs dynamic model. For example, the synchronization controller [3], robust controller [10], robust synchronization controller [11], etc. Additionally, the authors of [12] propose a dual-level hysteresis current controller for one five-leg VSI to control two PMSMs. However, it is noted that all of these previous works make the assumption that the system is fault-free. Actually, there is a high fault rate for these complex interconnected system, and the above assumption might be not true. Moreover, these controllers will not effectively work if the faults occur. To the best of the authors' knowledge, little researches on the fault diagnosis and FTC for these coupling two-PMSMs systems have been publicly reported. This motivate our present research.

As is well known, with the rapid development of science and technology, automation degree becomes more and more advanced, which makes a complete control system should contain the control unit, fault diagnosis unit and FTC unit. However, the traditional FTC is based on hardware redundancy [13,14]. It is not only costly and conservative, but also increases the volume and weight of the system. Then, some fault diagnosis and FTC strategies appear for various motor in Refs. [15–19]. Despite that these method can provide us with some ideas to design the fault-tolerant controller for two-PMSMs system, these methods only consider the sensors faults and ignore the actuators faults and components faults. Moreover, for the two coupling PMSMs systems, once a subsystem suffers from faults, the other subsystem will be influenced via the nonlinear coupling. That is, no matter what faults occur, these two motor subsystems will be in abnormal situation. But, the existing researches are concerned on the single PMSM system and don't consider the influences caused by the coupling between two motors. According to [20], the system affected by sensor faults can be rewritten as a system represented by actuator fault via a post-filter, and the component fault is similar to the actuator fault. That is to say, if the actuators faults tolerant controller can be designed for two-PMSMs systems, then all the system faults can be compensated by the similar method. Hence, how to predict the effect of actuators faults on the system and design the fault-tolerant controller are quite important for improving the system safety and reliability.

* Corresponding author.
E-mail address: xyanchu@csu.edu.cn (X. Chu).

https://doi.org/10.1016/j.isatra.2018.07.007
Received 4 September 2017; Received in revised form 28 May 2018; Accepted 11 July 2018

Please cite this article as: Xiong, H., ISA Transactions (2018), https://doi.org/10.1016/j.isatra.2018.07.007

On one hand, despite that there is only a few researches about fault diagnosis for coupling two-PMSMs systems, the two coupling PMSMs system is one of the nonlinear systems and a lot of efforts has recently been made on the fault diagnosis for nonlinear systems, such as sliding model observer (SMO) based fault estimation [21–23], fault detection and isolation based on unknown inputs observers (UIOs) [24,25], faults and states estimation based on adaptive observer in Refs. [26,27]. However, the discontinuous features for sliding mode observer can lead to the chattering phenomena [28]. Moreover, the upper of uncertainties are required. The UIO requires the unknown input distribution matrix must be known a priori [29]. Moreover, it can only realize that the faults are decoupled from the disturbances, and it cannot be utilized to reconstruct the system faults. Only the adaptive observer technique is proven simple design and easy implementation. And it is a useful tool to achieve the estimations of states and faults. Therefore, a large number of results about the adaptive observer and its application are published [30–32].

On the other hand, according to [33–37], the information of system faults are required when the fault-tolerant controllers are designed. Similarly, the design of synchronization fault-tolerant controller for two coupling PMSMs systems also require the system states and faults. The system states can be measured by physical sensors. However, it is difficult to obtain the faults by the same way. It makes the fault information-based FTC scheme ineffective. The above mentioned adaptive observer method can solve this problem. In addition, according to a large number of investigations, there is still no achievements concerning with FTC for coupling two-PMSMs systems. Therefore, it is necessary to design an appropriate fault-tolerant controller to realize the aim of synchronization control.

Based on the investigation above, we will focus on designing an adaptive observer-based fault tolerant controller for a class of coupling two-PMSMs systems. To design the fault-tolerant controller more conveniently, the idea of adaptive observer is utilized to obtain the estimation of the system faults. Then, the fault-tolerant controller is designed based on the estimated faults. It is also the first time that the adaptive observer based fault tolerant controller is used in such application. The main contribution of this paper can be summarized as follows:

(1) The dynamic model of two-PMSMs system with uncertain nonlinear coupling is presented firstly. Then, based on the system actuator faults presentation, the mathematical model of two-PMSMs system with actuator faults is given.
(2) An adaptive robust observer is designed to estimate the system states and faults simultaneously. Then, an adaptive observer-based robust state feedback fault-tolerant controller is proposed by using the LMI techniques and Lyapunov stability theorem.
(3) The designed observer and controllers via LMI can be easily solved. Moreover, the simulation results show that the adaptive observer can not only estimate the system states, but also can estimate the system actuator faults. The simulation results show that the designed fault tolerant controller can compensate the system faults with a high accuracy so that the system with actuator faults can track the given reference speed well.

The organization of this work is arranged as follows. Section 2, the two-PMSMs system with uncertain nonlinear coupling and actuator faults is presented. In Section 3, the adaptive robust observer-based robust state feedback fault-tolerant controller is designed. Then, the FTC algorithm design process is given. In Section 4, simulation is carried out via Matlab/Simulink soft. In Section 5, conclusions are presented.

2. Mathematical model

According to [9–11], the mathematical model of two coupling PMSMs can be given as

$$\begin{cases} \frac{di_{d1}}{dt} = -\frac{R_{s1}}{L_{d1}}i_{d1} + \frac{1}{L_{d1}}U_{d1} + \frac{L_{q1}}{L_{d1}}\omega_1 i_{q1} \\ \frac{di_{q1}}{dt} = -\frac{R_{s1}}{L_{q1}}i_{q1} - \frac{\Psi_1}{L_{q1}}\omega_1 + \frac{1}{L_{q1}}U_{q1} - \frac{L_{d1}}{L_{q1}}\omega_1 i_{d1} \\ \frac{d\omega_1}{dt} = \frac{3}{2}\frac{p_1\Psi_1}{J_1}i_{q1} - \frac{F_1}{J_1}\omega_1 - \frac{1}{J_1}T_{L1} - f_1(\theta_1-\theta_2) \\ \frac{di_{d2}}{dt} = -\frac{R_{s2}}{L_{d2}}i_{d2} + \frac{1}{L_{d2}}U_{d2} + \frac{L_{q2}}{L_{d2}}\omega_2 i_{q2} \\ \frac{di_{q2}}{dt} = -\frac{R_{s2}}{L_{q2}}i_{q2} - \frac{\Psi_2}{L_{q2}}\omega_2 + \frac{1}{L_{q2}}U_{q2} - \frac{L_{d2}}{L_{q2}}\omega_2 i_{d2} \\ \frac{d\omega_2}{dt} = \frac{3}{2}\frac{p_2\Psi_2}{J_2}i_{q2} - \frac{F_2}{J_2}\omega_2 - \frac{1}{J_2}T_{L2} - f_2(\theta_1-\theta_2) \end{cases} \tag{1a-f}$$

where, ω_n is the electrical rotor angular speed of motor n; i_{dn} and i_{qn} are $d-$ and $q-$axis stator currents of motor n; U_{dn} and U_{qn} are $d-$ and $q-$axis voltages of motor n respectively; R_{sn} is the stator resistance of motor n; L_{dn} and L_{qn} respectively are $d-$ and $q-$axis inductances of motor n; p_n is the number of poles of motor n; F_n is the viscous friction coefficient of motor n; Ψ_n is the magnetic flux of motor n; J_n is the rotor inertia of motor n; T_{Ln} is the load torque of motor n; θ_n is the rotor angular position of motor n; $f_n(\theta_1-\theta_2)$ is the nonlinear coupling force acting on motor n; and $n\in\{1, 2\}$; when the system is stable and the two motors are synchronous, the following formula is satisfied:

$$f_1(\theta_1-\theta_2) = -f_2(\theta_1-\theta_2) \quad and \quad \lim_{\theta_1-\theta_2\to 0} f(\theta_1-\theta_2) = 0 \tag{2}$$

The objective of fault tolerant control for two-PMSMs is to ensure the speeds of two motors track the desired speed. According to [9], the change of $d-$axis has little effect on system performance. Hence, only the actuator fault occurring in the $q-$axis are considered in the following section. Then, by considering external disturbances, the dynamic model of two coupling PMSMs system with actuator faults can be presented as:

$$\begin{cases} \dot{x} = Ax + Bu + \Phi(t,x) + Dd + Ef \\ y = Cx \end{cases} \tag{3}$$

where, $x = [i_{d1},\ i_{q1},\ \omega_1,\ i_{d2},\ i_{q2},\ \omega_2,\ \theta_1-\theta_2]^T$; $u = [U_{d1},\ U_{q1},\ U_{d2},\ U_{q2}]$; $\Phi(t,x)$ is the real nonlinear vector function satisfying the Lipschitz constraint; d represents the bounded external disturbance vector; f denotes the actuator fault; D and E are constant real matrices of appropriate dimensions;

$$A = \begin{bmatrix} -\frac{R_{s1}}{L_{d1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{R_{s1}}{L_{q1}} & -\frac{\Psi_1}{L_{q1}} & 0 & 0 & 0 & 0 \\ 0 & \frac{3}{2}\frac{p_1\Psi_1}{J_1} & -\frac{F_1}{J_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{R_{s2}}{L_{d2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{R_{s2}}{L_{q2}} & -\frac{\Psi_2}{L_{q2}} & 0 \\ 0 & 0 & 0 & 0 & \frac{3}{2}\frac{p_2\Psi_2}{J_2} & -\frac{F_2}{J_2} & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 & 0 \end{bmatrix};$$

$$B = \begin{bmatrix} \frac{1}{L_{d1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{L_{q1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_{d2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{L_{q2}} & 0 & 0 \end{bmatrix}^T;$$

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}.$$

Assumption 1. $\Phi(t,\ x)$ is assumed to be Lipschitz with a Lipschitz constant α_1, i.e.

$$\|\Phi(t,\hat{x}) - \Phi(t,x)\| \le \alpha_1\|\hat{x} - x\|$$