A PI fault tolerant method based on LQR for the electric motor servo system in Coal Mine

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Abstract: In this paper, against the fault diagnosis of mine motor servo system, a PI (Proportional and Integral, PI) fault tolerant method based on LQR (Linear Quadratic Regulator, LQR) method is proposed to solve the problem of parameter determination of PI fault-tolerant controller. In the proposed strategy, the proportional part is arranged in the feedback loop of the control system, so that the PI control law can be described in the form of system state feedback. And then the PI fault-tolerant control law is designed according to the PI control law. Finally, the scheme was applied to an electric motor in coal mine to demonstrate the effectiveness of the proposed fault estimation and diagnosis approach. Results of the simulation illustrate the effectiveness of the proposed method. The performance of the developed algorithm is tested and verified using the control model of an electric motor.

Keywords: PI control, fault tolerant method, the electric motor servo system, Coal Mine

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1.Introduction

Mine electromechanical servo system is one of the set of the mechanical and the electrical equipment, its regular task is the key to affect the normal work of coal mine. However, the mine electromechanical system equipment will inevitably experience three states in the use process, namely normal, abnormal and fault. If the equipment is abnormal, it indicates that the operation state of the motor has been deteriorated. The maintenance should pay attention to the motor. Once the development of the monitoring state develops to the fault state, it may cause serious accidents and even cause casualties. Therefore, it is of great significance to ensure the safe and reliable operation of the mine motor servo system.

In recent years, the fault-tolerant control method research targeted at the defective control system mainly has focused on the active fault-tolerant control and the passive fault-tolerant control [1-5]. Concurrently, as?for the motor in coal mine, the fault diagnosis methods have been studied by many authors. A fault diagnosis system with cerebellar model articulation controller was proposed for the smart induction motor [6]. The fault of induction motor was divided into three kinds: rotor mandrel fault, bearing fault and electrical fault. Meanwhile, the vibration signal spectrum of induction motor was analyzed to determine the single fault type. However, in practical engineering, the vibration signal of the induction motor was greatly affected because of the external interferences, which had a certain impact on the introduction motor fault diagnosis. Many researchers have studied the fault information in the control system by the fuzzy theory, and numerous strategies have been introduced. An approach for fault detection in unknown systems by fuzzy basis function network was presented in [7]. The unknown system was comprised of a known part, unknown part, and fault information. The unknown part, which includes the uncertainty of model error, disturbance, was estimated by a fuzzy basis function network, however, the fault information was not got in the real sense. In [8], a novel was designed fuzzy-based algorithm for the detection and diagnosis of drive faults

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in an induction motor drive system (IMDS). In this work, the efficacy of fuzzy logic was employed to characterize and diagnose the fault. In [9], a novel was approached based on an integrated fault estimator and state estimator for an electric motor in coal mine using a self-constructing fuzzy unscented Kalman filter (UKF) system. In the method, the self-constructing fuzzy UKF system was designed in order to obtain the fault information. According to fault information obtained fault detection experiments based on fuzzy clustering were performed with the proposed scheme and the fault feature parameters required for fault isolation were determined. However, the time-varying parameter perturbations corresponding to the nominal system matrices were not considered in the papers, and the limitations of the presented method was applicable to the model of the electric motor without the disturbances.

In order to accurately diagnose the fault of induction motor, a fault diagnosis of nonlinear observer method based on BP neural network and Cuckoo Search algorithm was proposed [7]. The induction motor model was divided into linear and nonlinear parts, and BP neural network was used to approximate the nonlinear part. At the same time, an adaptive observer was established, in which a simple and effective method for selecting the feedback gain matrix was offered. But in the proposed method, the fault information and the disturbances could not be divided in the nonlinear system. Thus, in order to obtain the fault information in the control system accurately, many scholars were devoted to the separation of fault and disturbance in the control systems. An adaptive Neural Fuzzy Petri Network Algorithm based on the traditional Petri net theory, fuzzy theory, and neural network algorithm was proposed for the diagnosis of motor faults [8]. Meanwhile, the transition confidence was replaced by a Gaussian function to solve the uncertainty of fault propagation. And combined with the BP neural network, fault diagnosis parameters are adaptively trained. In [9-10], the disturbance observer could be used to obtain the disturbances in the control systems. A finite time disturbance observer combined with nonsingular terminal sliding mode controller was proposed to estimate the uncertainty converges to the true value [9]. Similarly, in [10] the disturbance observer was designed to estimate the mismatch disturbance. On this basis a new fault tolerant control method is proposed for uncertain faults such as actuator sticking. In the above reference literature, although the disturbances of the control system could be estimated with the disturbance observer accurately, but the control system structure would be complex on account of the observer. Consequently, a fault-tolerant strategy with the simple structure has become the focus of fault-tolerant control theory, and it can adapt to the changes of various faults online. In?the?practical?industrial?process?control, since the traditional PID (Proportional, Integral and Differential, PID) control method has the characteristics of mature and reliable design method, simple structure, and less information requirement for the control system, it has become one of the most widely used classical control method. Some scholars also applied the PID control to the fault-tolerant control strategy of the defective system. A PID iterative learning fault-tolerant control law was designed for the continuous linear time-varying systems with actuator faults [11]. In the proposed method, the convergence condition of the fault-tolerant controller could be transformed into the linear matrix inequality to determine the optimal iterative control gain quickly, which avoided the blindness of setting the iterative control gain. In [12], aiming at the fault of redundant control actuator of aircraft, a fault compensation method based on PID extended state observer was adopted. In the proposed strategy, when the control system had fallen into the failure, the controlled system would start the compensation controller online, and compensated the influence of the fault on the controlled system as much as possible on the premise of ensuring the closed-loop stability of the controlled system. The problem of fault-tolerant control for a single link flexible manipulator with actuator effectiveness loss was studied in [13]. In the method, the adaptive law of the adaptive PID controller was derived by using the Lyapunov function, and then the adaptive PID controller was designed. The proposed controller could adjust the control gain of KP, KI and KD in real time to ensure the stability of the controlled closed-loop system under actuator failure. For the closed-loop control system with faults, the key to achieve the optimal control effect using the PID controller is to set and optimize the parameters of proportional, integral and differential parts, to obtain the nonlinear combination set of control variables, and then the optimal control scheme can be obtained.

A PI (Proportional and Integral, PI) fault tolerant method based on LQR (Linear Quadratic Regulator, LQR) method is proposed. In the proposed strategy, the PI controller is designed based on the control model of the mine electromechanical servo system. Firstly, the proportional part is arranged in the feedback loop of the control system in the method, so that the PI control law can be described in the form of system state feedback. Secondly, the PI fault-tolerant control law is designed according to the PI control law, and then the parameter matrix of the PI fault-tolerant controller can adapt to the fault changes in the motor control system. At last, the LQR control method is applied to the parameter determination of PI fault-tolerant controller to solve the problem of parameter determination of PI fault-tolerant controller.

2.Problem statements

In the paper, consider a control model of the electric motor servo system in coal mining in the following form [14]:

$$x(k+1) = Ax(k) + Bu(k) + w(k) \tag{1}$$

$$y(k) = Cx(k) + v(k) \tag{2}$$

Where $x(k)$ is the state vector, $x(k) \in R^n$. $u(k)$ Is the know control input, $u(k) \in R^n$ A,B,C are known time-varying real matrices and have appropriate dimensions. $w(k)$ and $v(k)$ are white noises sequences of uncorrelated Gaussian random vectors with zero means and covariance matrices Q and R respectively. $y(k)$ Is the output variables. In practical engineering, if the control object falls in failure, the control strategy will also be affected seriously. In the PID controller, the closed-loop control law is designed by combining compensator and controller, do as that, the optimal performance index of the closed-loop system can be determined. Therefore, to analyze the fault information of the control system accurately in the paper, the control law is designed according to the theory of PID closed loop-control. In the design of PI controller, the proportional part is arranged in the feedback loop of the control system, so that the PI control law can be described in the form of system state feedback. Thus, the control law is designed as following,

$$u_N(k) = K_p y(k) + K_I \sum_{i=0}^{k} (ref(i) - y(i)) \tag{3}$$

Where $ref(i)$ is the reference output vector of the electric motor servo control system, $ref(0) = 0$. K_p and K_I are the proportional parameter matrix and integral parameter matrix of the PI controller respectively. The PI controller block diagram of the motor servo control system is as following.

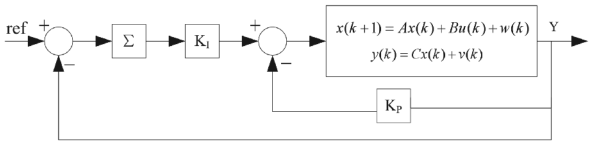

Fig. 1 The PI controller block diagram for the motor servo control system

The comprehensive error between the reference output and the actual controlled system output is assumed as,

$$e(k) = \sum_{i=0}^{k} (ref(i) - Y(i)) \tag{4}$$

Substituting Eq. (4) into Eq. (3), the control law can be further rewritten as following,

$$u_N(k) = K_p y(k) + K_I e(k) \tag{5}$$

In order to study the fault tracking and approximation of the electric motor servo system, in the next part, the control model of the electric motor servo system with the faults will be designed based on the Eq. (1).

Suppose the failure is happened in the input of an electric motor servo control system, the input of the control system of an electric motor in coal mining with faults can be represented as,

$$u_F^i(k) = \rho_k^i u_i(k) \tag{6}$$

where ρ_k^i i s the loss of the control effectiveness, $\rho_k^i \in [0,1]$. If $\rho_k^i = 1$, the control input is fault-free. If $\rho_k^i = 0$, the control input is outage. And then the matrix of the loss of the control effectiveness can be defined as,

$$\rho_k = \begin{bmatrix} \rho_k^1 & & & & \\ & \rho_k^2 & & & \\ & & \ddots & & \\ & & & \ddots & \\ & & & & \rho_k^n \end{bmatrix} \tag{7}$$

Based on Eq. (6), the input of the electric motor servo control system with faults can be further defined as,

$$u_F(k) = \rho_k u(k) \tag{8}$$

Substituting Eq. (8) into Eq. (1), an electric motor servo control model with faults can be defined as the following,

$$\tilde{x}(k+1) = A\tilde{x}(k) + B\rho_k\tilde{u}(k) + w(k) \tag{9}$$

$$\tilde{y}(k) = C\tilde{x}(k) + v(k) \tag{10}$$

Under the Fig.1 and the equations from Eqs. (9), (10), the PI controller block diagram of the motor servo control system with faults is as following.

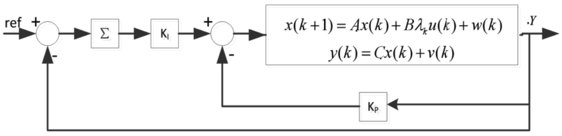

Fig. 2 The PI controller block diagram of the motor servo control system with faults It can be observed form the Eq. (1) and Eq. (9), to make the fault system approach the ideal system adaptively, the input of the fault system must be defined as,

$$\tilde{u}(k) = \rho_k^{-1} u_N(k) \tag{11}$$

The aim of this paper is to present an optimal fault tolerant method, which can simultaneously track the state with the failure and estimate the fault function of the electric motor control system. Simultaneously, the fault of the motor servo system is compensated to ensure the performance of the control system within a certain fault threshold. For the reason, in the next part the PI fault tolerant controller will be designed.

3.The PI fault tolerant controller design

For the sake of compensating the influence of fault on the normal work of the electric motor servo control system, a new fault control law is added to the normal controller to reduce the influence of fault on the electric motor servo control system. In this way, the running state of the electric motor control system can be tracked adaptively in the real time, and the desired control goal will be achieved by using the adaptive method. Aiming to the electric motor fault servo control system, an adaptive fault-tolerant control law is designed based on the normal control law (5) as shown in the following equation.

$$U(k) = u_N(k) + u_d(k) \tag{11}$$

Where u_d is the new fault control law. If $u_d = 0$, the electric motor servo control system is normal, but once $u_d(k) \neq 0$, the electric motor servo control system is in fault. At this time, the fault-tolerant controller will make the fault state asymptotically track the normal state, so as to ensure the performance of the fault electric motor servo system. Thus it can be seen that, it is particularly important how to design the fault-tolerant control law $u_d(k)$.

In order to design the new fault control law, based on the comprehensive error Eq. (4), the error of the electric motor servo fault control system can be defined as,

$$e(k+1) = e(k) - \tilde{x}(k) \tag{12}$$

To adaptively track the influence of fault on motor servo control system, combine the error of the electric motor servo fault control system Eq. (12) and the electric motor servo control system with faults and unknown inputs, the augmented discrete fault-tolerant control model of the electric motor servo system can be obtained as follows,

$$\begin{bmatrix} \tilde{x}(k+1) \\ e(k+1) \end{bmatrix} = \begin{bmatrix} A & 0 \\ -I & I \end{bmatrix} \begin{bmatrix} \tilde{x}(k) \\ e(k) \end{bmatrix} + \begin{bmatrix} B\rho_k \\ 0 \end{bmatrix} \tilde{u}(k) + w(k) \tag{13}$$

$$y_d(k) = \begin{bmatrix} I & 0 \end{bmatrix} \begin{bmatrix} \tilde{x}(k) \\ e(k) \end{bmatrix} + v(k) \tag{14}$$

In the above equation, make the following hypotheses as,

$$\tilde{A}=\begin{bmatrix}A & 0\\ -I & I\end{bmatrix}\quad \tilde{B}=\begin{bmatrix}B\rho_k\\ 0\end{bmatrix}\quad \tilde{C}=\begin{bmatrix}I & 0\end{bmatrix}\quad z(k)=[\tilde{x}(k)^T, e(k)^T]^T$$

The augmented discrete fault-tolerant control model of the electric motor servo system can be further described as,

$$z(k+1)=\tilde{A}z(k)+\tilde{B}\tilde{u}(k)+w(k) \tag{15}$$

$$y_d(k)=\tilde{C}z(k)+v(k) \tag{16}$$

Based on the augmented discrete fault-tolerant control system of the electric motor servo system, the adaptive fault-tolerant control law is defined as,

$$U(k)=\tilde{u}(k) \tag{17}$$

In the light of the Eq. (11) and Eq. (17), and then the following equation can be further obtained,

$$\begin{aligned}U(k)&=u_N(k)+u_d(k)\\ &=\tilde{u}(k)\end{aligned} \tag{18}$$

Rearranging of the above equation, the adaptive fault-tolerant control law can be expressed as,

$$u_d(k)=\tilde{u}(k)-u_N(k) \tag{19}$$

Substituting Eq. (5) and Eq. (11) into Eq. (19), the adaptive fault-tolerant control law can be further described as,

$$\begin{aligned}u_d(k)&=\tilde{u}(k)-u_N(k)=\rho_k^{-1}u_N(k)-u_N(k)\\ &=(\rho_k^{-1}-I)u_N(k)\\ &=(\rho_k^{-1}-I)(K_p\tilde{x}(k)+K_I e(k))\\ &=(\rho_k^{-1}-I)\begin{bmatrix}K_P & K_I\end{bmatrix}\begin{bmatrix}\tilde{x}(k)\\ e(k)\end{bmatrix}\\ &=(\rho_k^{-1}-I)\begin{bmatrix}K_P & K_I\end{bmatrix}z(k)\end{aligned} \tag{20}$$

So far, the derived expression of the fault-tolerant control law $u_d(k)$ is obtained as Eq. (19). In the derived expression, since the electric motor control system is affected by faults, it is difficult to determine the parameters of the fault-tolerant control law $u_d(k)$. Moreover, the parameter matrix K_p K_I of $u_d(k)$ are the multidimensional matrix. If the traditional experience debugging method is used to determine the parameters of $u_d(k)$, a large amount of calculation and the tedious workload will be caused. According to the literature, some scholars have used the discrete LQR control strategy to determine the parameter matrix of the system [17]. Therefore, in the following part, the discrete LQR control strategy will be used to determine the parameter matrixes of $u_d(k)$.

4.Solution of the parameter matrixes

According to the augmented discrete fault-tolerant control model of the electric motor servo system (15), by using the discrete LQR control method,?the?extremum problems?can be obtained,

$$\begin{cases}\min\limits_{\tilde{U}(k)} J=\dfrac{1}{2}\sum\limits_{k=0}^{n-1}[z^T(k)Qz(k)+\tilde{u}^T(k)R\tilde{u}(k)]\\ s.t.\ z(k+1)=\tilde{A}z(k)+\tilde{B}\tilde{u}(k)+w(k)\\ \qquad z(0)=z_0, k=0,1,\cdots,n\end{cases} \tag{21}$$

And then, based on the extremum problems, the Lagrange function can be defined as,

$$\begin{aligned}L&=J+\lambda^T(k+1)[\tilde{A}z(k)+\tilde{B}\tilde{u}(k)+w(k)-z(k+1)]\\ &=\frac{1}{2}z^T(n)Sz(n)+\frac{1}{2}\sum_{k=0}^{n-1}[z^T(k)Qz(k)+\tilde{u}^T(k)R\tilde{u}(k)]\\ &\quad+\lambda^T(k+1)[\tilde{A}z(k)+\tilde{B}\tilde{u}(k)+w(k)-z(k+1)]\end{aligned} \tag{22}$$

The following partial derivative functions can be obtained by calculating the partial derivatives of $\tilde{z}(k)$, $\tilde{u}(k)$, $\lambda(k)$ and let the result of each partial derivative function be zero respectively in Eq. (22).

$$\frac{\partial L}{\partial z(k)}=Qz(k)+\tilde{A}^T\lambda(k+1)-\lambda(k)=0 \tag{23}$$

$$\frac{\partial L}{\partial \tilde{u}(k)}=R\tilde{u}(k)+\tilde{B}^T\lambda(k+1)=0 \tag{24}$$

$$\frac{\partial L}{\partial \lambda(k)}=\tilde{A}z(k)+\tilde{B}\tilde{u}(k)-z(k+1)=0 \tag{25}$$

The control sequence of Lagrange function reaching the minimum can be gotten by solving equations (23) and (25) simultaneously. Meanwhile, the Riccati function is defined as,

$$P(k)=Q+A^{T}\%S[I+BR\%^{-1}B^{T}\%S]^{-1}A\% \quad (26)$$

The discrete control law of the electric motor servo system control model can be described based on the Riccati function.

$$\begin{aligned} u_d(k) &= -R^{-1}B^{T}\%\lambda(k+1) \\ &= -R^{-1}B^{T}\%(A^{T}\%)^{-1}\left[P(k)-Q\right]z(k) \\ &= -Kz(k) \end{aligned} \quad (27)$$

Rearranging of Eq. (27) and Eq. (20), the following equation can be obtained,

$$u_d(k)=-Kz(k)=(\rho_k^{-1}-I)\left[K_P \quad K_I\right]z(k) \quad (28)$$

And then, based on the above equation, the parameter matrixes of $u_d(k)$ can be obtained as,

$$\left[K_P \quad K_I\right]=-(\rho_k^{-1}-I)^{-1}K \quad (29)$$

In?conclusion, the multivariable PI fault-tolerant control is equivalent to state feedback fault-tolerant control of multivariable augmented system, and then the parameter matrix of multivariable PI fault-tolerant control law is solved by using the discrete LQR theory. In next section, an electric motor will be taken as an example to illustrate the usefulness of the PI fault tolerant method based on LQR method.

5.Simulation

verification In this section, the continuous-time model of the electric motor servo system is described by [9],

$$J\frac{d\omega(t)}{dt} = -b\omega(t) + k_i i(t) \quad (30)$$

$$\frac{d\theta(t)}{dt} = \omega(t) \quad (31)$$

$$\frac{di(t)}{dt} = -\frac{R_a}{l_a}i(t) - \frac{k_b}{l_a}\omega(t) + \frac{u(t)}{l_a} \quad (32)$$

and the constraint equation is given by,

$$R_a i(t) + k_e\omega(t) = au(t) \quad (33)$$

The variables in the above equations and the parameters of the electric motor servo system can be given as Table 1,

Table 1 Electric motor parameters

Symbols	Symbols Meaning	Values in simulations
J	the moment of inertia of the motor shaft	0.01 kgm^2
b	the coefficient of viscous friction	0.05Nms
K_e	the back electromotive force constant	0.25V/rad s^{-1}
K_i	the back torque constant	0.25Nm/A
R_a	the motor armature resistance	2Ω
a	the amplification constant	20
l	the motor armature inductance	2H
ω	the rotor speed	0.176rad s^{-1}

In the simulations we took no heed of the disturbance From R_a, a, b, and assumed that the armature inductance is zero. According to Eqs. (31), (32) and (33), the continuous-time control model of the electric motor servo system can be described as,

$$\begin{bmatrix}1&0&0\\0&J&0\\0&0&1\end{bmatrix}\begin{bmatrix}i\&\\ \omega\&\\ \theta\&\end{bmatrix}=\begin{bmatrix}-\frac{R_a}{l_a}&\frac{k_e}{l_a}&0\\k_i&-b&0\\0&0&1\end{bmatrix}\begin{bmatrix}i\\ \omega\\ \theta\end{bmatrix}+\begin{bmatrix}\frac{1}{l_a}\\0\\0\end{bmatrix}u(0) \quad (34)$$

The output current of the electric motor servo system will be changed while it is in the fault. Consequently, we can get the motor's fault information through the output current. Meanwhile, the output equation of the control system can be defined as,

$$y = [1 \;\; 0 \;\; 0]\begin{bmatrix}i\\ \omega\\ \theta\end{bmatrix} \quad (35)$$

Based on the Euler's forward method, the continuous-time electric motor model of the electric motor servo system can be further discredited to yield a discrete-time descriptor system form as follows:

$$\begin{bmatrix}\frac{1}{T}&0&0\\0&\frac{J}{T}&0\\0&0&\frac{1}{T}\end{bmatrix}\begin{bmatrix}i(k+1)\\ \omega(k+1)\\ \theta(k+1)\end{bmatrix}=\begin{bmatrix}\frac{1}{T}-\frac{R_a}{l_a}&\frac{k_e}{l_a}&0\\k_i&\frac{1}{T}-b&0\\0&0&\frac{1}{T}\end{bmatrix}\begin{bmatrix}i(k)\\ \omega(k)\\ \theta(k)\end{bmatrix}+\begin{bmatrix}\frac{1}{l_a}\\0\\0\end{bmatrix}u(0) \quad (36)$$

$$y(k) = [1\ 0\ 0]\begin{bmatrix} i(k) \\ \omega(k) \\ \theta(k) \end{bmatrix} \quad (37)$$

Where T = 1 is the sampling time. Here, assuming the follow equations as,

$$E = \begin{bmatrix} \frac{1}{T} & 0 & 0 \\ 0 & \frac{J}{T} & 0 \\ 0 & 0 & \frac{1}{T} \end{bmatrix} \quad A = \begin{bmatrix} \frac{1}{T} - \frac{R_a}{l_a} & \frac{k_e}{l_a} & 0 \\ k_i & \frac{1}{T} - b & 0 \\ 0 & 0 & \frac{1}{T} \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{l_a} \\ 0 \\ 0 \end{bmatrix} \quad C = [1\ 0\ 0]$$

$$x(k) = [i(k)\ \ \omega(k)\ \ \theta(k)]^T$$

Then, the continuous-time control model of the electric motor servo system can be rewritten as,

$$Ex(k+1) = Ax(k) + Bu(k) \quad (38)$$

$$y(k) = Cx(k) \quad (39)$$

In the above equations E is the full rank matrix, therefore, multiplying both sides of Eq. (38) b E^{-1} , and the equation can be further expressed as,

$$x(k+1) = E^{-1}Ax(k) + E^{-1}Bu(k) \quad (40)$$

To monitor the fault of the electric motor, we assume that the input is affected by an additive fault. According to Eq. (8), the continuous-time control model of the electric motor with failure as follow,

$$x(k+1) = E^{-1}Ax(k) + E^{-1}Bu(k) + f(k) \quad (41)$$

where $f(k) = -E^{-1}Bu(k)\gamma_k, 0 \le \gamma_k \le 1$.

In order to strengthen its practicality and flexibility, in the application, we assume that the input voltage $u(0)$ Is affected by an additive actuator fault, and the angular position $\theta(k)$ is affected by an additive sensor fault. Here, all the state variables are measurable. In the simulations, the system matrices of the electric motor model can be given as,

$$A = \begin{bmatrix} 0 & 0.25 & 0 \\ 0.5 & 0.75 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad B = \begin{bmatrix} 0.25 \\ 0 \\ 0 \end{bmatrix} \quad C = [1\ 0\ 0] \quad u(0) = 220$$

The covariance matrices Q and can be given as,

$$Q = \begin{bmatrix} 1.220 & 0 & 0 \\ 0 & 1.220 & 0 \\ 0 & 0 & 1.220 \end{bmatrix} \quad R = 0.125$$

The input of the system can be given as,

$$x(0) = [10.124\ \ 1.142\ \ 2.140] \quad (42)$$

In the paper, the value of the failure rate ρ can refer to Reference [9]. Based on LQR method, and according to Eq. 29, under the condition of $\rho = 0.5$, the proportional parameter matrix Kp and the integral parameter matrix KI of the PI fault-tolerant control can be further obtained as Table 2 and Table 3:

Table 2 The proportional parameter matrix KP

K_P	1	2	3
1	3.427	-4.822	-2.441
2	-2.082	1.197	-0.422
3	1.837	-1.577	-3.098

Table 3 The integral parameter matrix KI

K_I	1	2	3
1	-1.363	1.811	0.911
2	0.718	-0.437	0.156
3	-0.617	0.549	1.088

Thus, the parameter matrixes of $u_d(k)$ can be obtained according to the proportional parameter matrix KP and the integral parameter matrix K_I. With the proposed method in the paper, the motor servo fault control system will be adjusted to ensure the normal operation of the electric motor under the faults. The effect is shown in the following figure.

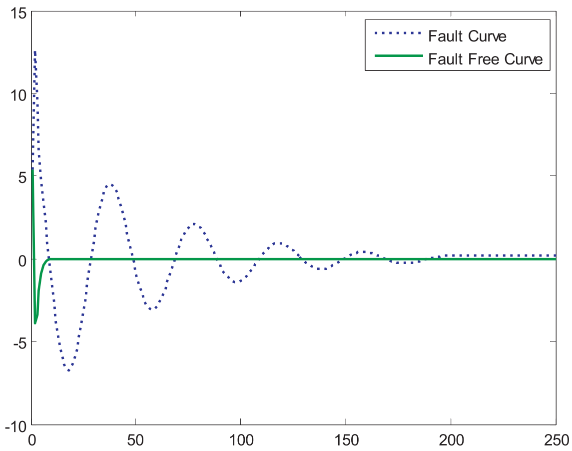

Fig. 1 Fault Curve

As seen in Fig. 1, since the occurrence of the faults are caused by many factors, the fault curve, which is got with the proposed method, is the?oscillation?curve. Before the Step 200, the current fault curve is overshooting of the system, which shows the state of the electric motor is in the critical failure. It is shown that the fault information of the system states can be got with high precision by the proposed method in this paper through the Fig. 1.

To validate the proposed method, the failure rate will be changed as $\rho = 0.8$. By using the similar method to the above, the proportional parameter matrix KP and the integral parameter matrix K_I of the PI fault-tolerant control can be further obtained as Table 4 and Table 5:

Table 4 The proportional parameter matrix KP

K_P	1	2	3
1	-3.098	0.996	-10.844
2	1.990	-4.153	-8.238
3	-3.647	3.561	-14.452

Table 5 The integral parameter matrix KI

K_I	1	2	3
1	4.715	3.665	2.574
2	-4.275	-7.041	8.948
3	2.901	-2.383	6.738

According to the proportional parameter matrix Kp and the integral parameter matrix K_I, the parameter matrixes of $u_d(k)$ can be obtained. With the proposed method in the paper, the motor servo fault control system will be adjusted to ensure the normal operation of the electric motor under the faults. The effect is shown in Fig. 2.

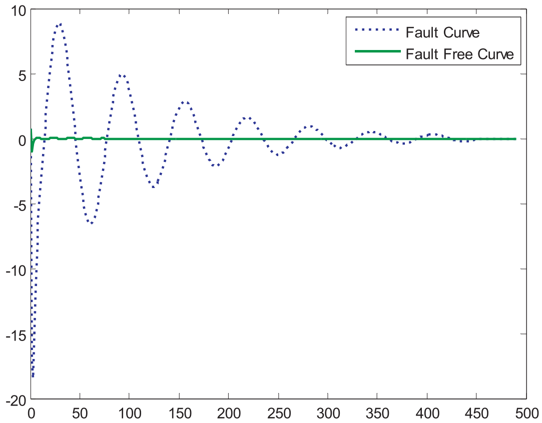

Fig. 2 Fault Curve

As seen in Fig. 2, due to the increase of the failure rate of the electric motor, the failure curve has a strong fluctuation. With the increase of the failure rate, the fault curve fluctuates strongly, but under the control adjustment of the proposed method, after 450 iterations, the fault curve is gradually converged to the ideal state. It is shown that It is shown that the normal operation of the electric motor can be ensured under the faults.

6.Conclusion

In this paper, the PI fault tolerant method based on LQR method is proposed to solve the problem of parameter determination of PI fault-tolerant controller for the electric motor in coal mine. First, based on the PID theory, the proportional part is arranged in the feedback loop of the control system, so that the PI control law can be described in the form of system state feedback. Second, the PI fault-tolerant control law is designed according to the PI control law. Finally, the scheme was applied to an electric motor in coal mine to demonstrate the effectiveness of the proposed fault estimation and diagnosis approach. Results of the simulation illustrate the effectiveness of the proposed method. The performance of the developed algorithm is tested and verified using the control model of an electric motor.

Furthermore, the time-varying parameter perturbations corresponding to the nominal system matrices were not considered in this paper, and the limitations of the presented method is applicable to the model of the electric motor without the disturbances. Future research will consider a self-constructing fuzzy system to approach the fault function with the parameter perturbations.

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