Fault tolerant control of electric pitch control system based on single current detection

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Abstract: In view of the current sensors failure in electric pitch system, a variable universe fuzzy fault tolerant control method of electric pitch control system based on single current detection is proposed. When there is single or two-current sensor fault occurs, based on the proposed method the missing current information can be reconstructed by using direct current (DC) bus current sensor and the three-phase current can be updated in time within any two adjacent sampling periods, so as to ensure stability of the closed-loop system. And then the switchover and fault tolerant control of fault current sensor would be accomplished by fault diagnosis method based on adaptive threshold judgment. For the reconstructed signal error caused by the modulation method and the main control target of electric pitch system, a variable universe fuzzy control method is used in the speed loop, which can improve the anti-disturbance ability to load variation, and the robustness of fault tolerance system. The results show that the fault tolerant control method makes the variable pitch control system still has ideal control characteristics in case of sensor failure although part of the system performance is lost, thus the correctness of the proposed method is verified.

Key words: electric pitch control; fault tolerant control; variable universe fuzzy control; single current detection

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With the gradually increase of unit capacity, large wind turbine generally adopts variable pitch control technology. Variable pitch system is the core component of variable pitch controlled wind turbine, and its reliable operation not only affects service life, operation and maintenance cost of the wind turbine, but also has a huge impact on the safe and stable operation of power grid[1]. As a result of long-term operation in the heavy-moisture and high-dust circumstances and the complexity of self-structure, the control performance of electric pitch system may become ineffective due to the possible failure of different components of the system. Because current sensor is one of the weak links in the vector control system of variable pitch motor, when there is bad contact or sensor disconnection, it will cause significant damage. The variable pitch system can reduce hardware redundancy and complexity of the system as much as possible on the premise of meeting the requirements of reliability and safety, therefore it is of great significance to study the fault tolerant control of current sensor in variable pitch system[2-3].

At present, the methods of current reconstruction mainly include model method and modulation method. The model method is based on the accurate mathematical model of the motor and it can obtain the three-phase current relying on other physical quantities such as voltage. In Ref.[4], the three-phase current of the motor is estimated by using the accurate mathematical model of the motor and the rotor position information, and the current sensor is also cancelled. In Ref.[5], two parallel Romberg bilinear current observers are built according to the mathematical model of the motor, and the estimated value

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of the observer is used to replace the measured value to realize the redundancy operation under current sensor fault circumstances. The disadvantage of the model method is that it relies on too many motor parameters, which decreases the robustness of the control system. The modulation method can sample two-phase current information to reconstruct three-phase current within one switching period by using direct current (DC) bus current sensor. This method is more valuable without increasing the cost of the system. The various error sources of the modulation method are analyzed in Ref. [6]. In Ref. [7]. the modulation method is used to reconstruct the current signal and the proportion-integration-differentiation (PID) controller is used to eliminate the error caused by the reconstructed signal. It is very difficult for PID algorithm to obtain ideal performance. The general fuzzy controller dossesses proportion-differentiation (PD) control characteristics but has disadvantages relatively lower control accuracy and adjustment dead zone, and so on.

The main control objective of fault tolerant control for electric pitch is the speed control of variable pitch motor, and the anti-disturbance ability is also supposed to be considered simultaneously. In order to solve the above problems, in this paper, the variable universe fuzzy control algorithm[8] is applied to the speed control of the electric pitch system to change parameters of the controller in case of current sensor fault, and then the fault tolerant control of the variable pitch system is realized.

1 Electric pitch servo system

Electric pitch system selects alternating current (AC) asynchronous motor as driving mechanism. Based on indirect vector control method of rotor flux linkage orientation and combined with the space vector pulse width modulation (PWM) technology, the control scheme of electric pitch system is designed by three closed-loop controls of current, speed and position.

Under normal pitch control circumstances, to obtain good tracking performance required by current loop, proportion-integration (PI) controller is usually used. The speed control of pitch is one important link in electric pitch control system, to improve anti-disturbance ability and inhibit speed fluctuation, the fuzzy control method is adopted. Position loop uses traditional proportion (P) controller to adjust the position of pitch angle for fast and non-overshooting tracking of expected value. The structure of the electric pitch servo system based on indirect vector control is shown in Fig. 1.

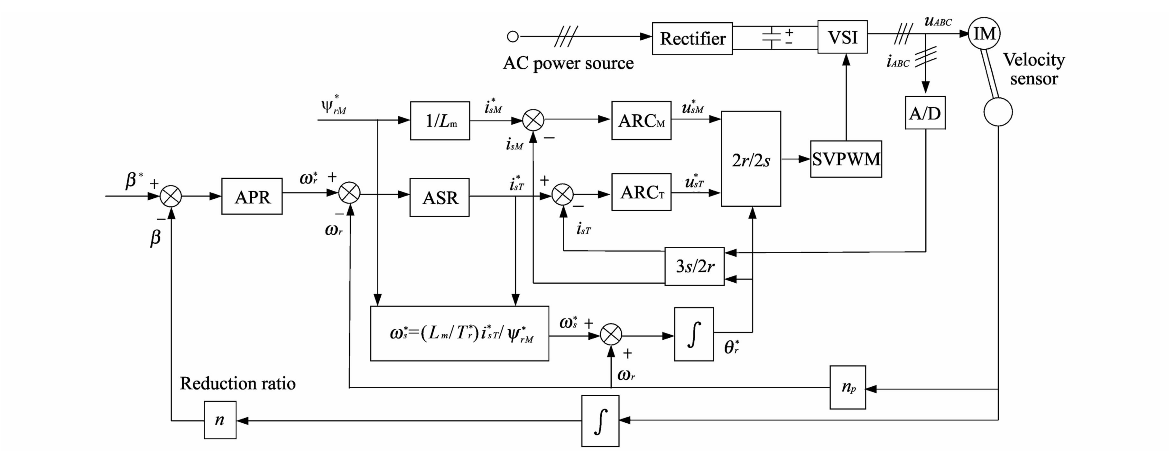


Fig. 1 Structure diagram of indirect vector control of electric pitch servo system

2 Sensor fault tolerance of pitch system

2.1 Reconstruction of current sensor

When there is single or two current sensor faults in electric pitch system, the DC bus current sensor is used to reconstruct the missing current information, and software reconstruction method can be used to meet the requirements of fault tolerant control without increasing the cost of the system.

The realization of asynchronous motor phase current reconstruction is as follows: firstly obtaining the AC side phase current indirectly by DC side current sensor detecting bus current and accomplishing the detection of two phase alternating currents within one control period, and then calculating the third phase current according to the characteristic that the sum of three phase currents is zero. The typical SVPWM-VSI three-phase full-bridge inverter is shown in Fig. 2.

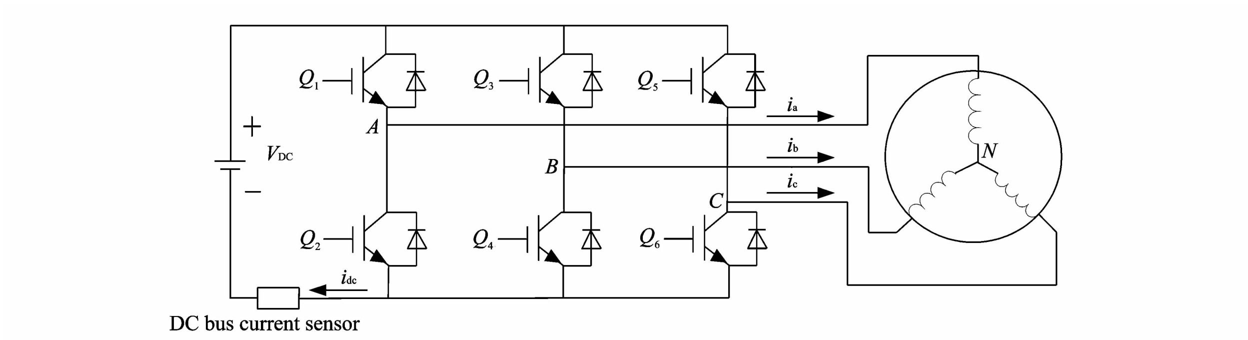


Fig. 2 Three-phase inverter

Six power devices in three bridge arms generate a total of eight switching states, including two zero vectors and six effective vectors. S_a, S_b and S_c are used to represent the switching states of the three bridge arms, respectively. If the high-side bridge arms of a, b and c phase conduct electricity and the lower bridge arms are cut off, the expression is $S_a=1$, $S_b=1$ and $S_c=1$. On the contrary, if the high-side bridge arms are cut off and the lower bridge arms conduct electricity, $S_a=0$, $S_b=0$ and $S_c=0$. There by the relationship between the switching states of the inverter and the voltage space vectors can be got, as shown in Fig. 3[9-10], where $V_i=(S_a, S_b, S_c)$, $i \in \{0,1,2,\cdots,7\}$.

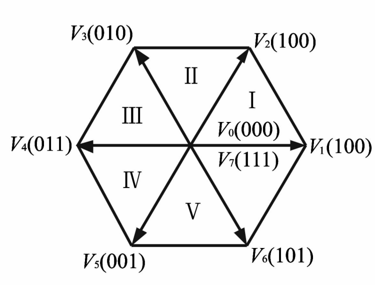


Fig. 3 Space voltage vector

When three bridge arms are different states, there is a definite relationship between the DC bus current of the inverter and three-phase current of the asynchronous motor. For different voltage space vectors, the relationship is shown in Table 1.

Table 1 DC bus current vector space under different voltages

Voltage space vector	DC bus current
V_0(000)	0
V_1(100)	$+i_a$
V_2(110)	$-i_c$
V_3(010)	$+i_b$
V_4(011)	$-i_a$
V_5(001)	$+i_c$
V_6(101)	$-i_b$
V_7(111)	0

2.2 Fault tolerant control strategy of current sensor

The fault types of the sensor are divided into hard fault and soft fault according to its fault degree. Thereinto, hard fault, with large output amplitude change, is generally caused by damage of sensor components, strong pulse interference, etc.; Soft fault, with small and slow output amplitude change, is mainly caused by aging of the components and zero drift. In this paper, the fault tolerant control strategy of the current sensor constructed by fault diagnosis of adaptive threshold is adopted, as shown in Fig. 4.

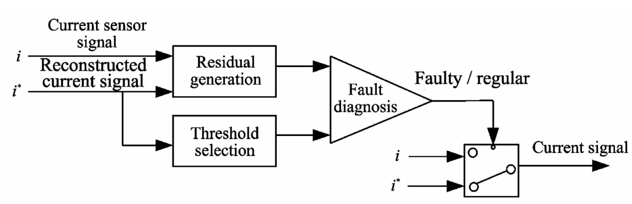


Fig. 4 Fault-tolerant control diagram of rotor current sensor

The steps of the fault diagnosis are as follows:

1) Obtain the residual of fault by comparing the output values of current sensor and the reconstructed module;

2) Take proper proportion output value of the reconstructed module as the adaptive threshold of fault diagnosis;

3) Judge whether any sensor fault occurs by comparing the residuals with the adaptive threshold.

The selection of the threshold will affect the accuracy of fault diagnosis. At present, the method of fixing the threshold is usually used in many articles[11]. As a result, fault diagnosis model usually does not adapt to dynamic process. Because the maximum current that inverter can withstand is three times the rated value in general, and considering that the threshold parameters are influenced by model bias and unknown noise, when the current exceeds 20% of its rated value, the sensor as is regarded failed. Therefore, this paper chooses 0.2 times of output value of the current reconstruction module on line as reference threshold, and the threshold parameters change adaptively with the output signal of the reconstruction module.

3 Fault tolerant control of variable pitch system

The value of the DC current within each sampling period is measured based on the analysis above and the phase current is updated according to the current switching state of the power device and the relationship shown in Table 1. Because only one phase current is updated each time, in order to reduce influence of estimation error during current reconstruction and effective estimation error during the freewheeling periods of the diode on fault tolerant of variable pitch system, the variable universe fuzzy control algorithm is adopted.

3.1 Theory of variable universe

In Ref. [12], the essence of fuzzy controller is an interpolator. To make the fuzzy control function obtained by interpolation can sufficiently approximate the real control function, on the one hand, the distance between the peaks of the fuzzy sets should be close enough, on the other hand, the control rules should be as many as possible. But it is difficult to be realized for fuzzy controller to summarize the control rules only relying on domain expert knowledge. Aiming at the low accuracy of the fuzzy controller and the contradiction between the number of rules in domain and the control precision, variable universe fuzzy control is introduced. On the premise of not changing the form of fuzzy control rules but changing the initial universe of the fuzzy controller by selecting appropriate contraction-expansion factor of the universe, the initial universe can follow the change trend of the error, that is to say, they increase or decrease together. By looking this partially observed from the local angle, contraction of the universe means that the distance between the peaks of the fuzzy set in a domain is closer. This increases the control rules and variables of fuzzy language, which can approximate the ideal control function more accurately the control precision. The schematic diagram of variable universe is shown in Fig. 5.

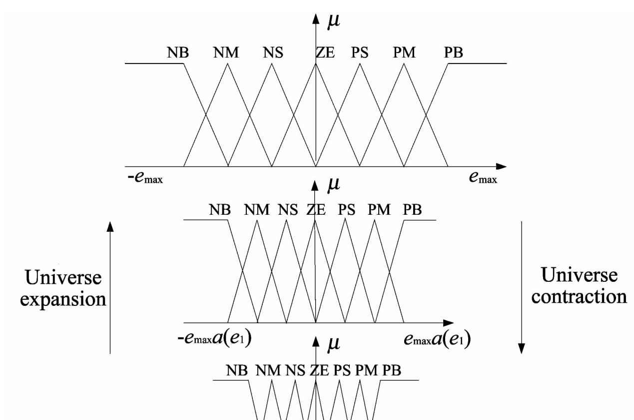


Fig. 5 Schematic diagram of variable universe

3.2 Contraction-expansion factor of variable universe

For a given fuzzy controller the input variable is x_i ($i=1,2,\cdots,n$), and the range of the corresponding universe X_i is $[-E,E]$; output variable is y and the range of the corresponding universe Y is $[-U,U]$. E and U should be positive real number. $A_i=[A_{ij}]$($j=1,2,\cdots,m$) is the fuzzy set division of X_i, and $B=$

$\{B_j\}$ ($j=1,2,\cdots,n$) is the fuzzy set division of Y. Regard A_i and B as linguistic variables, and the following fuzzy rules can be obtained:

If x_1 is A_{1j}, x_2 is A_{2j}, and x_n is A_{nj}, then y is B_j.

Let the peak points of A_{ij} and B_j be x_i and y ($i=1,2,\cdots,m$, $j=1,2,\cdots,n$), respectively, and the changes of x_i and y will cause the changes of universe X_i and Y. The mathematical expression is

$$X_i(x_i) = [-\alpha_i(x_i)E_i,\ \alpha_i(x_i)E_i], \tag{1}$$

$$Y(y) = [-\beta(y)U,\ \beta(y)U], \tag{2}$$

where $\alpha_i(x_i)$ ($i=1,2,\cdots,m$) and $\beta(y)$ are the corresponding contraction-expansion factors of the universe.

Reasonable selection of contraction-expansion factor can improve the precision of the control system. When the function of contraction-expansion factor $\alpha_i(x_i)$ is determined, the conditions that should be satisfied firstly are as follows[13]:

1) monotonicity: α_i monotonically increasing strictly at a closed interval of $[0,E]$;

2) Zero-preservation: $\alpha_i(0)=0$;

3) Duality: $\forall x_i \in X_i \alpha(x_i)=\alpha_i(-x_i)$;

4) Coordination: $\forall x_i \in X_i \alpha_i(x_i)=\alpha_i(-x_i)$;

5) Normality: $\alpha_i(\pm E)=1$.

Double-input single-output fuzzy control system is designed in this paper. Let V be the universe of error e, W be the universe of error rate e_c, and Y be the universe of output y. The range of the input universe is $[-E,E]$ andthe output universe is $[-u,u]$, the contraction-expansion factor of three variables are a, b, u. Because the error rate depends on the error, namely, there is an inherent connection between V and W, b is defined in $V\times W$, namely $b=b(e,e_c)$. Considering that proportional contraction-expansion factor not only has the performance of simple operation, but also can greatly simplify the algorithm compared with integral contraction-expansion factor, in order to meet the conditions of normal contraction-expansion factor, the structure of ratio index contraction-expansion factor[14] is built as

$$\begin{cases} \alpha(x) = \left(\dfrac{|e|}{E}\right)^{\tau_1}, \\ b(e,e_c) = \left[\left(\dfrac{|e|}{E}\right)+\left(\dfrac{|e_c|}{E}\right)\right]^{\tau_2}, \\ c(y) = \left(\dfrac{|y|}{u}\right)^{\tau_3}. \end{cases} \tag{3}$$

According to the requirements of the pitch system, the actual design of the variable universe fuzzy controller of speed loop is realized by using S function. Firstly, select ratio index contraction-expansion factor in Eq. (3); Secondly, take the error e and error rate e_c between given rotor speed and actual feedback speed of the motor as inputs of the controller; Finally use Matlab Simulink Toolbox to build variable universe fuzzy controller of speed loop.

4 Simulation analysis

Matlab/Simulink toolbox is used to build electric pitch simulation model, as shown in Fig. 6.

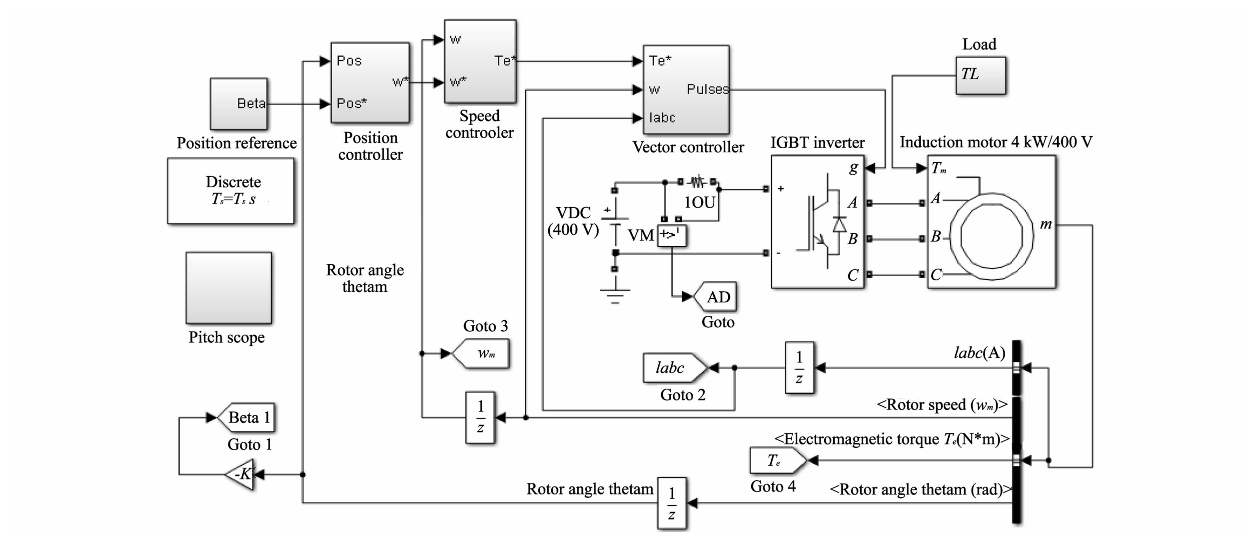


Fig. 6 Simulation structure diagram

Speed loop adopts variable universe fuzzy controller, and the simulation diagram is shown in Fig. 7. The variable universe fuzzy control program is also accomplished.

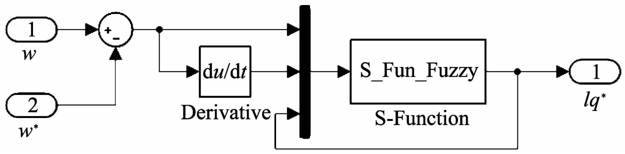


Fig. 7 Structure of variable universe fuzzy controller

The parameters of asynchronous motor for electric pitch actuator include rated voltage: 400 V; rated power: 4 kW; rated speed: 1 430 r/m; rotor resistance: 1. 395 Ω; stator resistance: 1. 405 Ω; stator and rotor leakage inductance: 0. 005 839 H; mutual inductance between stator and rotor: 0. 172 2 H. The maximum moment of resistance of 1 mW wind turbine acting on the executive motor in different cases is 11. 19 N • m. Therefore, in the simulation test, the given load torque of the executive motor is required to change below 11. 19 N • m. Taking $T_s = 2\times10^{-6}$ s as sampling time of the system, load torque of the execute motor changes according to 8 N • m→11 N • m→5 N • m.

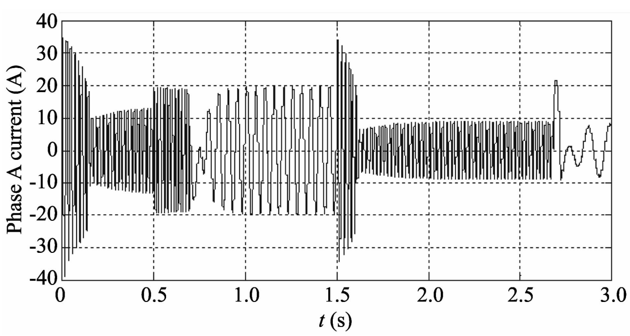


Fig. 8 Phase A current curve of execute motor stator in a normal situation

When the current signal is reconstructed, the sample of DC bus current is supposed to be completed firstly. Without changing the amplitude of the current signal, the value of sampling resistance is 1 Ω. Then the output signal of three phase current can be obtained, by using the sector judgment signal N, output modulation wave and the sampling signal of DC bus current in space vector pulse width modulation (SVPWM) module as the input of reconstruction module. Phase A current curves of the execute motor are shown in Figs. 8—9, which are obtained in a normal situation, and fault situation respectively.

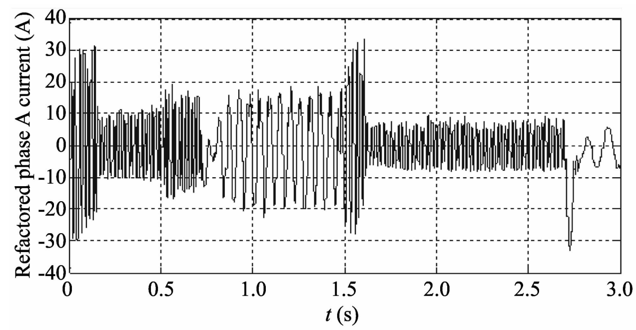
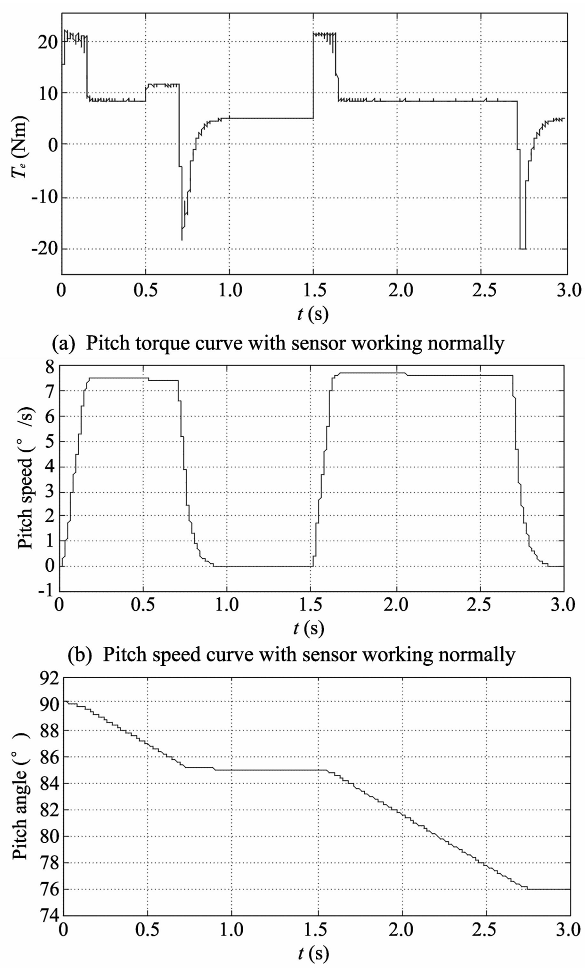


Fig. 9 Constructed phase A current curve of execute motor stator in fault situation

Figs. 10—11 represent pitch torque curves, pitch speed curves and pitch position tracking curves of the executing motor, which are obtained in a normal situation and current sensor fault situation based on intelligent fault tolerant control of single current detection.

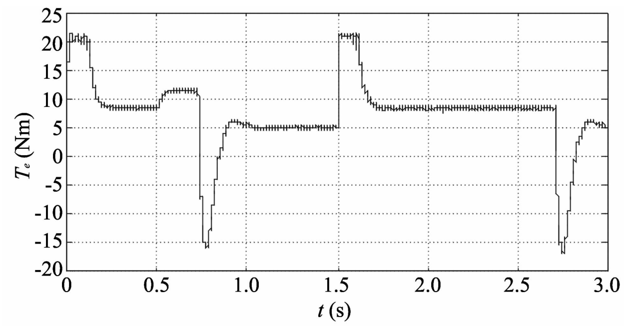


(a) Pitch torque curve with sensor working normally

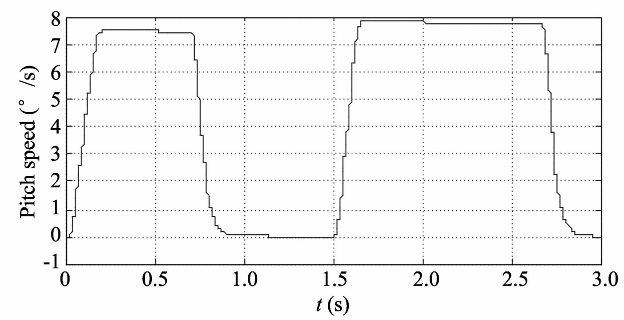
(b) Pitch speed curve with sensor working normally

(c) Pitch position curve with sensor working normally

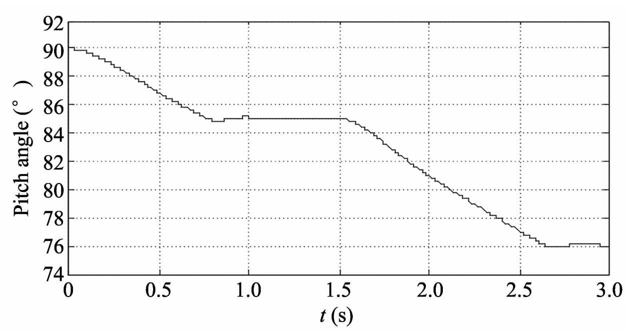
Fig. 10 Pitch curve with sensor working normally



(a) Pitch torque curve under sensor fault tolerant control

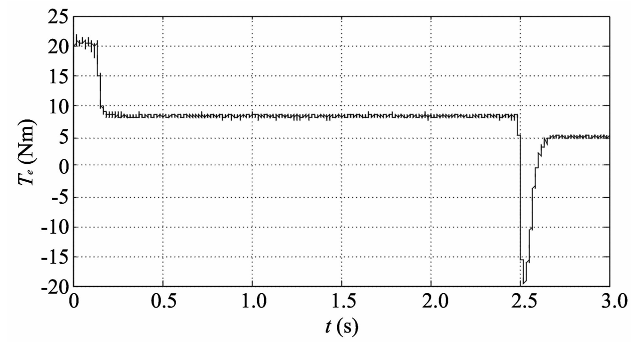


(b) Pitch speed curve under sensor fault tolerant control

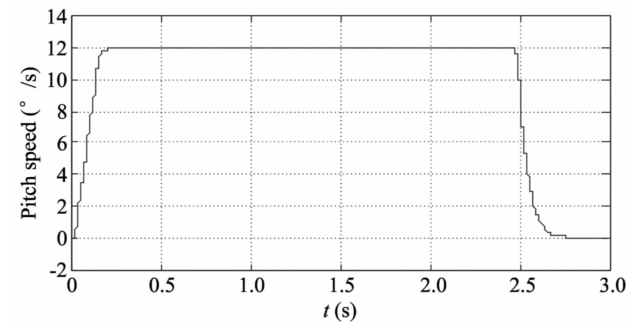


(c) Pitch position curve under sensor fault tolerant control

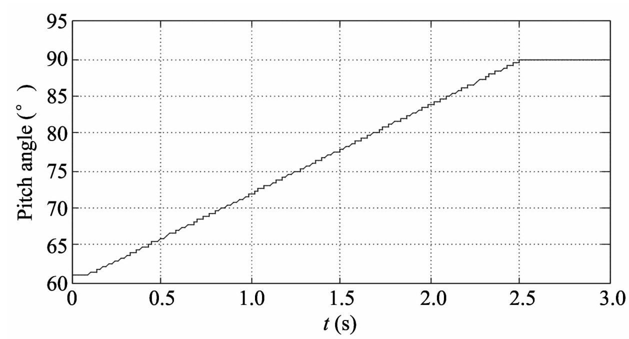
Fig. 11 Pitch curves under sensor fault tolerant control



(a) Emergency pitch torque curve under sensor fault tolerant control



(b) Emergency pitch speed curve under sensor fault tolerant control



(c) Emergency pitch position curve under sensor fault tolerant control

Fig. 12 Emergency pitch curve under sensor fault tolerant control

By analyzing the simulation results in two cases, when current sensor fault occurs, the torque ripple of the execute motor based on variable universe fuzzy tolerant control algorithm of single current detection is limited to the fluctuation range, which is less than 1 Nm. When sudden change of the execute motor load occurs, the pitch speed curve fluctuates as well, with the pitch speed change of 0.3 °/s compared with normal pitch speed 7.5 °/s and the corresponding pitch position tracking curve also overshoots slightly. Fig. 12 shows that the emergency pitch adjustment of 12 °/s can be realized in sensor fault situation. On the premise that this fault tolerant method sacrifice part of the performances of the control system, the safe and reliable operation of the electric pitch control system is guaranteed, and fast and accurate tracking of the pitch angle is also realized.

5 Conclusion

In this paper, aiming at the influence of current sensor fault of electric pitch system, estimation error during current reconstruction and the effective estimation error of phase current during the freewheeling periods of diode on the pitch fault tolerant system, the variable universe fuzzy intelligent fault tolerant control method is proposed. When current sensor fault of the execute motor occurs, the use of modulation method to reconstruct the three-phase current signal can guarantee that the closed-loop system is still stable. The speed loop is introduced into the variable universe fuzzy controller to inhibit reconstruction signal error and improve the system ability to resist load disturbance. The control performance of the torque output, pitch speed and position tracking of the variable pitch motor is decreased to some extent, but it still has ideal output characteristics. Safe and reliable operation of the electric pitch system is effectively ensured, and robustness and reliability of the system are improved as well.

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基于单电流检测的电动变桨系统容错控制

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摘　要： 针对电动变桨系统中常见的电流传感器故障，提出一种基于单电流检测的电动变桨系统变论域模糊容错控制方法。当变桨系统发生单个或两个电流传感器故障时，该方法利用直流母线电流传感器对所缺失的电流信息进行重构，保证三相电流能在任意两个相邻采样周期内得到及时更新，确保闭环系统稳定，并通过自适应阈值故障判断法完成故障相电流传感器的切换及容错。针对调制法引起的重构信号误差及电动变桨系统的主要控制目标，将变论域模糊控制方法应用于速度环，以改善系统抗负载扰动能力，提高容错系统鲁棒性。结果表明，该容错控制方法使得变桨系统在传感器故障情况下，牺牲部分系统性能后依然具有较理想的控制特性，并且该方法的正确性也得到了验证。

关键词： 电动变桨；容错控制；变论域模糊控制；单电流检测

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