A Fault-tolerant Drive System of Active Magnetic Bearing

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***Abstract*—The non-contact magnetic bearings are widely used in high-speed rotating machinery. As the safety issue is one of the priorities of the whole system, in this paper, a fault-tolerant drive system is proposed. The proposed drive system with full-bridge converter architecture has two modes: the normal mode and the auxiliary mode. It can ride-through the open-circuit failure of power electronics devices in the drive and keep levitation. Failure of power electronics devices can be detected through the winding current in the magnetic bearing. Experimental results are provided in this paper to validate the failure detection and fault-tolerant control capability with levitation.**

I. INTRODUCTION

In the high-speed drives industry application, the non-contact magnetic bearings have superior capability over the conventional mechanical bearings due to the advantages such as frictionless, wear-free, no-lubrication and low loss [1]~[3]. The basic principle of the active magnetic bearing (AMB) is shown in Fig.1. The position sensor detects the deviation of the rotor position from the reference position, then the controller sends the current signal to the power amplifier, and the power amplifier derives the control current of the electromagnetic. Finally the electromagnetic generates the electromagnetic force to suspend the rotor in the reference position.

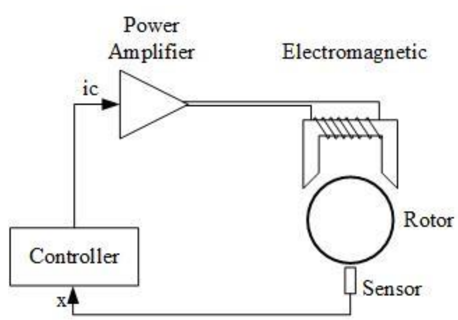

Fig.1 The schematic of magnetic bearing of one-axis

To levitate a whole rotor shaft, two magnetic bearings are applied in this system, for an eight poles C type bearing, it has two pairs of windings, and each pair of windings shares one power amplifier as is shown in Fig.2. The control of two axes in the magnetic bearing is through the current in ia1-ic1 and ia2-ic2.

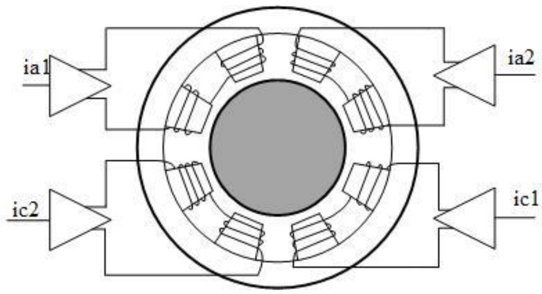

Fig.2 An eight-poles bearing and its windings

And the electromagnetic force can be calculated as

$$f = \frac{\mu_0 N^2 A I_0}{s_0^2} i_c - \left(-\frac{\mu_0 N^2 A I_0^2}{s_0^3} \right) x = k_i i_c - k_x x \qquad (1)$$

Where μ_0 is magnetic permeability of vacuum, I_0 is the constant bias current in winding, N is the number of the turns of the winding, A is the cross sectional area of the airgap, s_0 is the length of the airgap, k_i is the current stiffness coefficient and k_x is the displacement stiffness coefficient.

In order to generate precise and fast response current in the winding of AMB, power amplifier, or AMB drive is needed. Power electronics converters are the new generations of AMB drives. The traditional drive modules to generate the magnetic winding current are full H-bridge, half H-bridge and three phase half bridge [4]~[5]. The drive topology of three half bridge converter for a pair of windings is shown in Fig.3. With the DC bus voltage, the winding current in the pair of windings can be controlled in unidirectional by switching of three active power electronics switches and three freewheeling diodes.

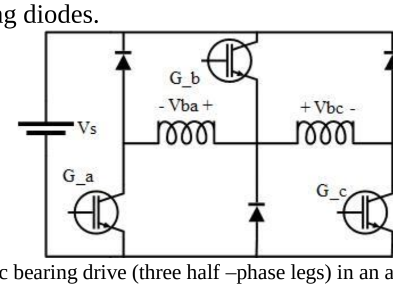

Fig.3 Magnetic bearing drive (three half –phase legs) in an axis

However, considering the full system reliability, the power electronic devices are very fragile and the sudden failure of the switching elements during the high speed operation process can cause a sudden change of winding current, which will totally destroy the steady state of the system and cause severe damage. Based on the security consideration. Considering the power electronics failure in AMB drive, device open-circuit failure is a major failure type. It can be happened with disconnection of wire ond in the device package. When this failure happens in any of the power electronic switches in Fig.3, the current control capability for the corresponding winding will be lost and the levitation in the corresponding axis will be damaged.

A new drive system with fault tolerant function is proposed. It can maintain the system stability when open-circuit failure occurs and shut down the whole system when short-circuit failure happens.

In this digest, the proposed drive system will be discussed and analyzed in Section II. In the Section III, the experiment results will be presented to demonstrate the effectiveness of the proposed method.

II. THE FAULT TOLERANT CONTROL OF MAGNETIC BEARING

There are two aspects of a fault tolerant system, first, the redundancy in the actuator. Second, the controller is able to detect the fault and adjust the control method to compensate for the fault [6].

A. *The Power Electronic Drive of The Fault-tolerant System*

For the whole four-axis magnetic bearing system, two eight poles magnetic bearings are used, and each owns four windings. In the conventional drive system, every two windings share one converter, with the structure shown in Fig.4.

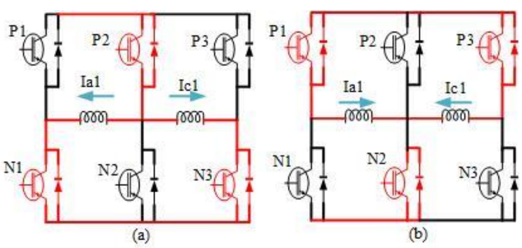

Fig.4 The power electronic drive for each axis. (a):The normal mode, with P2, N1,N3 (in red color) activated while the rest are blocked;(b):The auxiliary mode, with P1,P3,N2 activated and P2,N1,N3 are all blocked

The electronic fault-tolerant magnetic drive module is constructed as full-bridge three-phase converter, it includes two pluralities of switching elements (P2, N1, N3) and (P1, P3, N2). The red labeled devices in Fig.4 (a) can control the current in the "backward" direction and called normal mode. The red labeled devices in Fig.4 (b) can control the current in the "toward" direction and called auxiliary mode. Because the magnetic force is not related to current direction, both of those two modes can generate controllable force on the rotor and suspend the rotor in the reference position. Fig.5 shows the control diagram of the active magnetic bearing system. The outer loop is position PID control loop, and the inner loop is current loop using PI control.

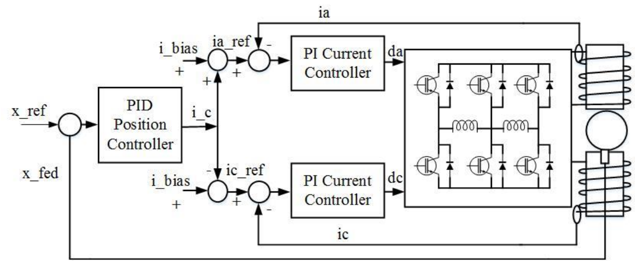

Fig.5 The control diagram of AMB in one-axis

While the converter switching from the normal mode to the auxiliary mode, the direction of the winding current changes opposite, but the electromagnetic force will remain the same [7].

Fig.6 shows the PWM logical signals of the converter controlled in the normal mode, N1, P2, N3 are activated while the rest are blocked. With the switching of N1, P2 and N3, winding current can be controlled in "backward" direction. Fig.7 shows the windings current and the rotor position, the rotor will be controlled in reference position within 6ms.

Simulation result shows that both two modes can suspend the rotor shaft well.

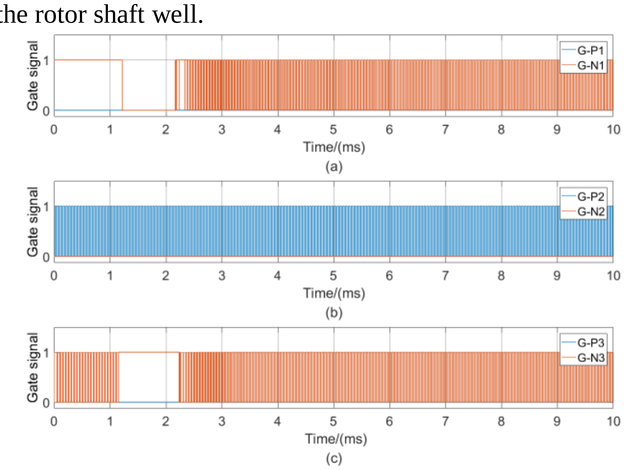

Fig.6 The PWM signal of the converter controlled in normal mode

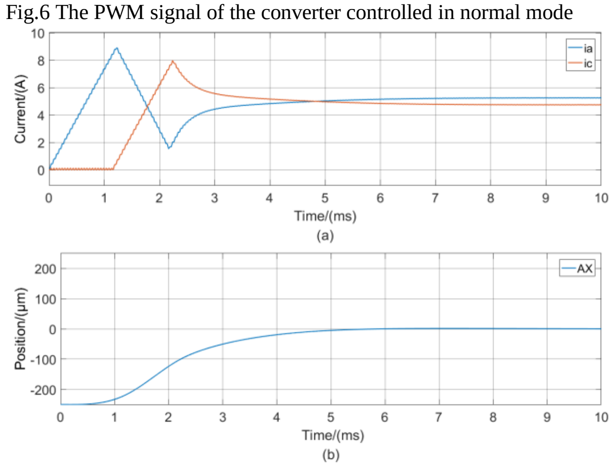

Fig.7 Windings current and rotor position controlled in normal mode

Fig.8 shows the PWM signals controlled in the ausiliary mode, P1, N2, P3 are activated and the rest are blocked; As shown in Fig.9, the direction of winding current is reversed but the absolute value is exactly the same as the the windings current controlled in the normal mode. And the control effect of the rotor has no difference with the normal mode.

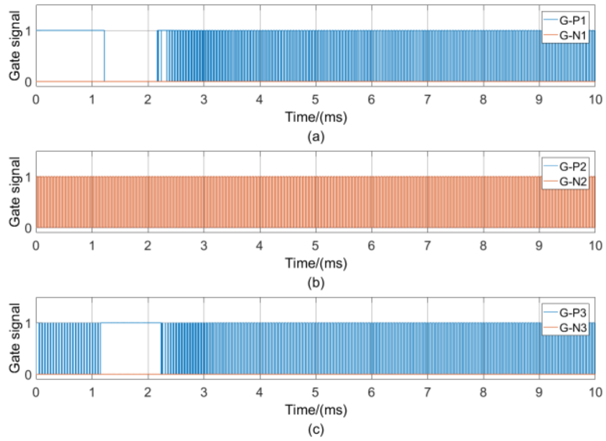

Fig.8 The PWM signal of the converter controlled in auxiliary mode

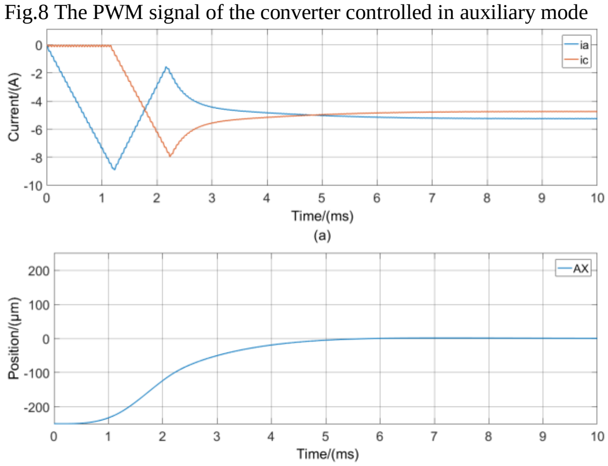

Fig.9 Windings current and rotor position controlled in auxiliary mode

B. *The Fault Detection Module*

In normal operation, the sum of the two winding current in each axis will be constant as double of the bias current. Two common events of the switching element fault are over current error and open-circuit error, and each error will result in a sudden change of the winding current, so the switching elements fault can be detected by judging the total value of the current of each pair of winding. The total current value is almost twice bigger than the bias current, and two threshold value *I_limit1* (upper one) and *I_limit2* (lower one) shall be chosen properly, for example, if the value of the bias current is 5A, then the total value of a pair of windings should be near 10A. For *I_limit2*, if it is too close to 10A, since there are current ripples in the winding current, the total value of the windings current may be lower than 10A at a certain time, and that may lead to a faulty operation of the whole system; While if *I_limit2* is too small, it will take more time before the fault identification module detects that fault, and the electromagnetic force will recover slowly, that can cause a crash between the shaft rotor and the touch-down bearing. With all those considerations, in this case, we choose *I_limit2* to be 9A and for the same cause, the value of *I_limit1* is 11A. If the total current value exceeds *I_limit1*, a short-circuit fault is detected and the system should be shut down; If the total current is lower than *I_limit2*, then an open-circuit is detected and the drive module can be switched from the normal mode to the auxiliary mode and keep the bearing suspension; Otherwise, the drive module would operate at the normal mode. The fault detection process is shown in Fig.10.

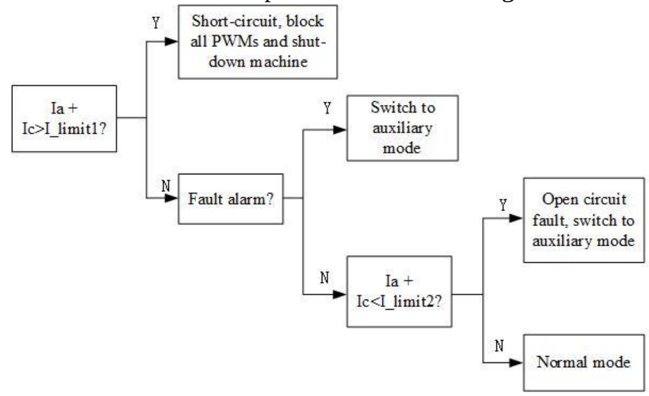

Fig.10 The flow diagram of fault detection [7]

The implementation of this fault-tolerant control method in magnetic bearing system is shown in Fig.11. The outer loop is position control loop, the inner loop is current control loop. The reference position and the rotor position will be sent to the position controller, and then the position controller send out the current signals to the circuit controller. Because the winding current direction of the auxiliary mode is opposite comparing with the normal mode, the output reference current signal should take the opposite value before they are sent to circuit controller of the auxiliary mode. The circuit controller will output the duty cycles to the PWM module and generate two sets of PWM signals. The winding current signals are send to the fault detection module. The fault identification module detects the failure and determines the working modes of the full-bridge converter. If it is the auxiliary mode, the PWM signals of the auxiliary mode will be chosen to activate the IGBTs of the power amplifier; If an short-circuit fault is detected, the system would block down all the IGBTs; Otherwise, the normal mode PWM signals will be sent to the power electronic drive. The power amplifier derives real currents and generate the electromagnetic force to levitate the rotor. If open-circuit failure happens in the levitation with normal mode, the winding current detection module will identify the failure in short period and active the fault-tolerant control by change the PWM to auxiliary mode. The AMB will reverse the winding direction current and keep levitation.

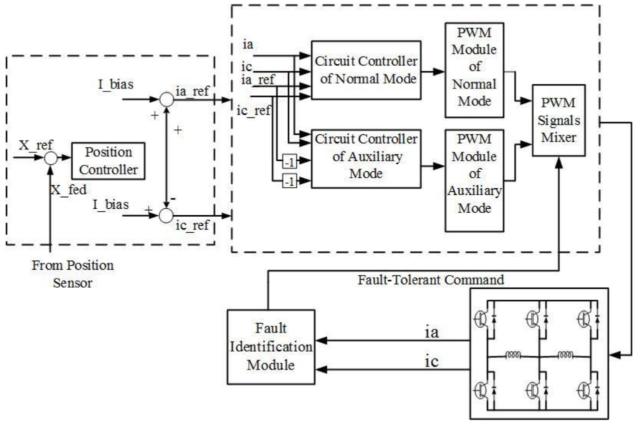

Fig.11 The fault-tolerant system diagram [7]

C. *The Simulation Result of the Fault Tolerant Control*

Simulation has been done to validate the effect of the fault tolerant control system. And the main parameters of the simulation are listed in Table.1.

TABLE I. MAJORITY PARAMETERS OF THE SIMULATION

Symbol	Variable	Value
Touch down bearing airgap	g_0	250µm (total 500µm)
Magnetic bearing gap	s_0	500µm
DC voltage for the converter	V_{DC}	150V
Bias current	I_bias	5A
Switching frequency	fs	20kHz
The upper threshold value	I_limit1	11A
The lower threshold value	I_limit2	9A
Turns per coil	N	46
Cross sectional area of a pole	A	2e-3m^2
Mass of the rotor	m	10Kg

The simulation results of the transient process of the open-circuit fault tolerant control are shown in Fig.12. Fig.12 (a) shows the PWM gate signals of IGBT P1 and N1. At 1ms, P1 is shut down to simulate the open-circuit fault of the switching elements, it can be found in Fig.12 (b) that the windings current starts to decrease, when the total value of ia and ic is lower than I_limit2, the fault identification module identifies that fault and sends a signal to switch the power electronic drive from normal mode to auxiliary mode. Fig.12 (a) indicates that right after the open-circuit failure of P1, N1 is activated and the current begins to flow in reverse, finally, the absolute value is the same as it was controlled in the normal mode; Fig.12 (c) indicates that the position of the rotor begins to fall down after the open-circuit fault, but when the power electronic drive switches from the normal mode to the auxiliary mode, the electromagnetic force recovers quickly and can suspend the rotor at the central position finally, and the max amplitude of the rotor position fluctuation is less than 15µm.

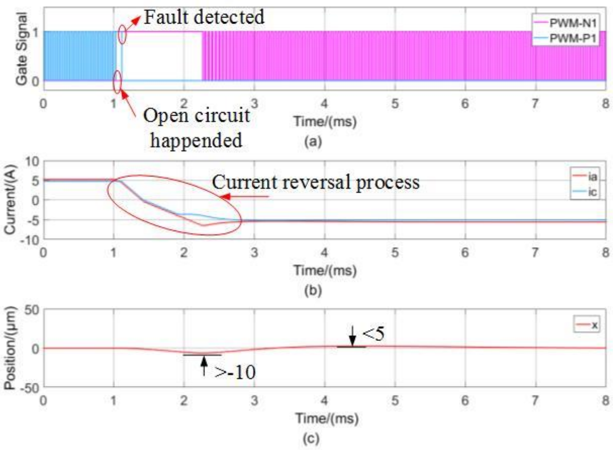

Fig.12 The open-circuit fault tolerant control

III. EXPERIMENT RESULTS

In order to validate this fault-tolerant control method, a four-axis magnetic bearing test rig has been developed, four eddy-current transducers are used as position sensor to detect the rotor position. The adaptive board is used to convert the voltage level of the signal from the position sensor, then output the analog signal to the AD channel of the control board, the DSP will calculate the digital signal and figure out the duty cycle and send out the PWM signal of each IGBT of the drive circuit board. The drive circuit board outputs the winding current, then the bearing can generate the electromagnetic force to levitate the rotor stably. The drive motor connects the rotor through a coupling and pull the rotor rotating at a certain speed. The independent PID control for each axis has been applied in this four-axis magnetic bearing. The implement of the four-axis magnetic bearing system is shown in fig.13.

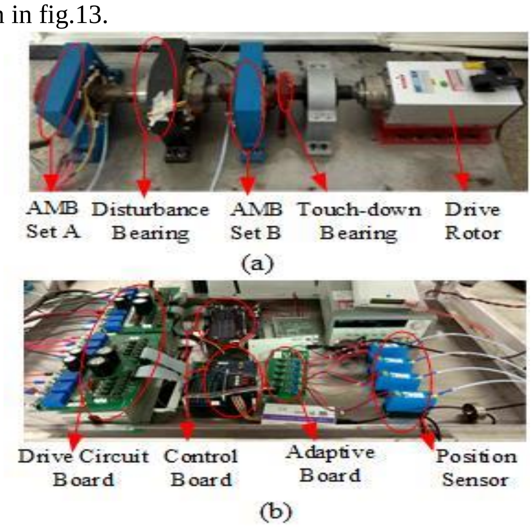

Fig.13 The implement of the magnetic bearing system. (a):The test rig;(b):The control module.

Some important variables and their value are shown in table 2.

TABLE II. MAJORITY PARAMETERS OF THE TEST RIG

Symbol	Variable	Value
Touch down bearing airgap	g_0	250μm (total 500μm)
Magnetic bearing gap	s_0	500μm
DC voltage for the converter	V_{DC}	150V
Bias current	I_bias	5A
Switching frequency	fs	20kHz
The upper threshold value	I_limit1	11A
The lower threshold value	I_limit2	9A

Experiments have been done in various situations. At first, the rotor is suspended at zero speed. After the rotor suspension steadily, an open-circuit fault happens and the fault tolerant control of the system starts to work. It turns out that without fault-tolerant control, when device open-circuit error happens, the current control capability is lost and the position control will fail and make the shaft drop and touch down, as shown in Fig.14 (a). With the fault-tolerant control method, the current control capability will be kept by switching from normal mode to auxiliary mode. The position of AX and AY axis will be controlled in zero after a short transient period, as shown in Fig.14 (b).

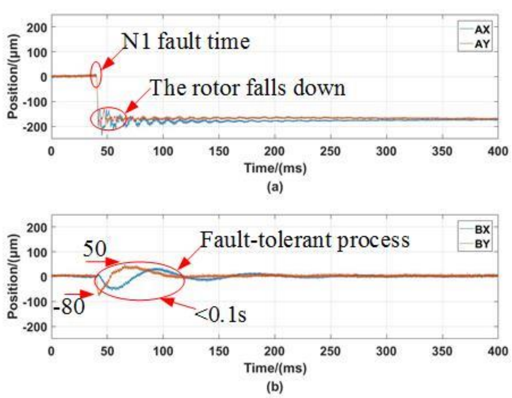

Fig.14 The result of switching elements open-circuit fault. (a):without fault-tolerant control;(b) with fault-tolerant control.

The PWM gate drive signals of the failure IGBT and the auxiliary IGBT along with the transient process of the windings current are shown in Fig.15. G-N1 is turned off at t1 to emulate a device open-circuit error. The winding current will drop. After a short period, open-circuit fault has been detected and G-P1 is activated to switch the bearing to auxiliary mode. The winding current will be controlled in the reversed direction finally.

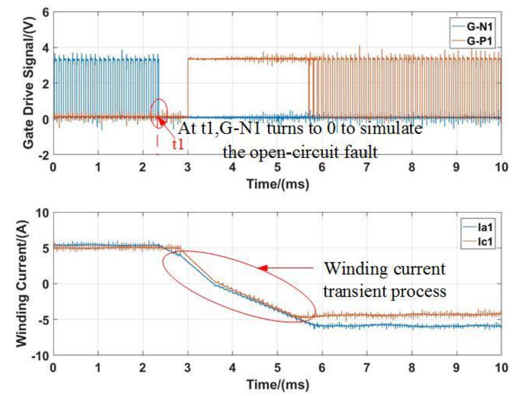

Fig.15 (a): The PWM signals of N1 and P1; (b): the transient process of the winding currents

When the rotor is suspended steadily at the speed of 600 rpm, at time t2, shows in Fig.16 (a), PWM-N1 is turned off to emulate the open-circuit fault of the device, and the winding current starts to decrease, then within 0.5ms, the fault has been detected and the power electronic drive switches to the auxiliary mode, and the windings current starts to reverse as shown in Fig.16 (b). The rotor position is shown in Fig.17, besides the lost control of the windings current, the synchronous disturbance caused by the rotor rotation can also affect the rotor position, and since the transient process of the fault tolerant control is very fast as well the inertia of the rotation, the change of the rotor position caused by the open-circuit fault is not obvious during the whole process. The rotor position of the fault tolerant control at a different speed is shown in Fig.18. Since the fault tolerant control reacts so quickly, the displacement of the rotor position caused by the open-circuit fault can be covered during the whole suspending process, the ripples of the rotor position are mainly caused by the disturbance of the rotation. And the reversal process of windings current at different speed is shown in Fig.19.

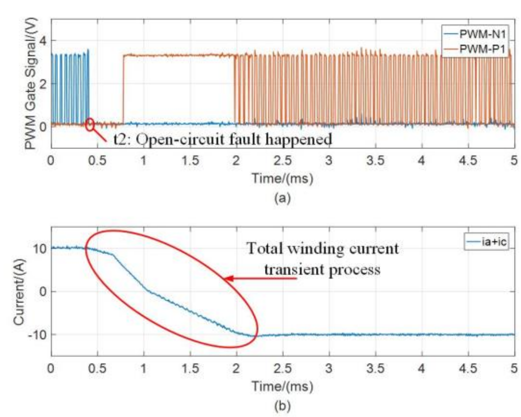

Fig.16 (a): The PWM signals of N1 and P1 (at 600 rpm); (b): the transient process of the winding currents (at 600 rpm)

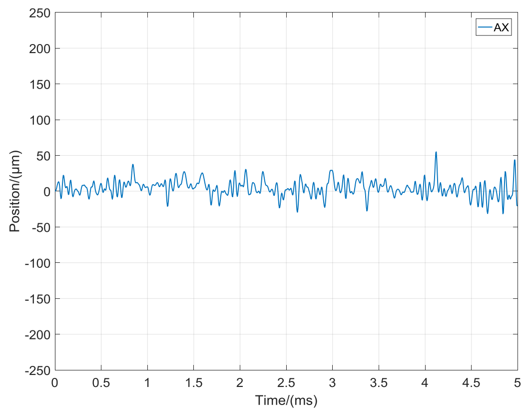

Fig.17 The result of open-circuit fault with fault tolerant control (600rpm)

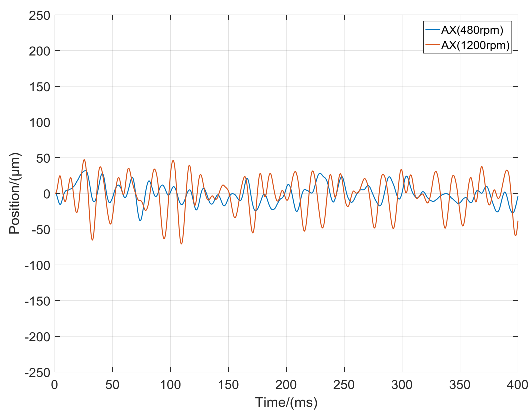

Fig.18 The result of open-circuit fault with fault tolerant control at speed 480rpm and 1200rpm

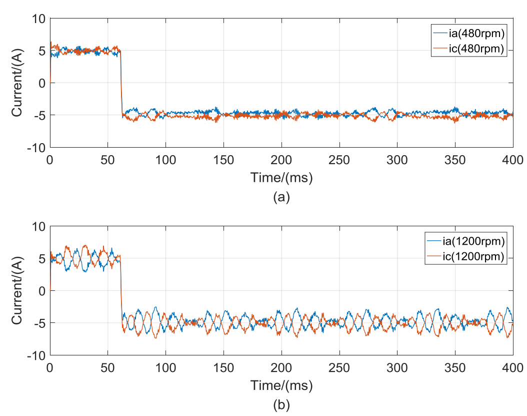

Fig.19 The transient process of the windings current at the speed of 480 rpm and 2000 rpm

IV. CONCLUSION

This paper introduces a fault-tolerant magnetic bearing drive. By utilizing this drive and control method, the system can detect switching element faults quickly and command the drive module to switch to the auxiliary mode so that the system can stay stability with power electronics device open circuit failure. Both simulations and experiments have been done to validate the performance of this novel fault-tolerant system, and results turns out this fault tolerant control can detect the open-circuit error quickly and switch to the auxiliary mode to keep the rotor suspend steadily.

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