Short-Circuit Fault-Tolerant Strategy for AMB Power Electronic Controller Based on Shared-Bridge Topology

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Abstract

Short-circuit faults of power electronics devices are major reason for active magnetic bearing (AMB) system failures, posing a serious threat to system stability, especially during high-speed rotor rotation. Despite this, very few studies have explored switch short-circuit fault-tolerance in AMB system. To address this issue, this paper introduces a fault-tolerant control strategy for short-circuit faults in switching devices, based on shared-bridge topologies. Two set of shared-circuit topologies are used separately to control one coil of each axis, once the short circuit happens, the coils controlled by the faulty shared-bridge topology are controlled to constant current, while the coil controlled by the normal shared-bridge topology are controlled to bias current and control current. In addition, the current must to be reversed to ensure the controllability of the faulty shared-bridge topology. The method also includes short-circuit fault detection. Relevant fault-tolerant experiments have been done to verify the effectiveness of the proposed approach. This approach provides high reliability for AMB system even with the power electronics devices short circuit failure.

Keywords: *Active magnetic bearing, Power electronic controller, Short-circuit fault, Fault-tolerant control*

1. Introduction

The non-contact active magnetic bearings (AMB) are widely used in high-speed rotating machinery, as centrifugal compressors, flywheel energy storage and so on. In the above applications, reliability is undoubtedly a key performance indicator, and the fault-tolerant control is an effective way to improve that [1]. In order to solve the reliability of actuators, Maslen provides the mathematical basis for bias current linearization of magnetic bearing in [2]. This kind of approach is applied to various kinds of magnetic bearing [3]. Many scholars have also studied the method of magnetic bearing fault detection. A fault identification based on discrete time wavelet coefficients is presented in [4]. Cheng et al. [5] provides a fault-diagnosis method based on the equivalent slope of current. However, there are few studies on the fault tolerant control of power amplifiers.

In reference [6], the survey results show that power electronic devices in the converters are the most vulnerable component to fail, there are mainly fault types such as open circuit and short circuit, caused by overheating, overvoltage or overcurrent, etc. Reference[7] provided a reliable switching amplifier, which consists of two or more left and right hand half-bridges. The abundant redundancy of the half-bridge enables it to deal with open or short-circuits of switching devices. However, it doubles the number of switching devices, which significantly increases the cost and size of the amplifiers, and switching off the damaged half-bridge is also an additional burden. In order to solve this problem, reference [8] proposes an open-circuit fault-tolerant control strategy for AMB power electronic controller and fault-tolerant experiments had been carried out at different speed conditions, this fault tolerant method not only reduce the number of switching devices, but also makes the fault tolerant switching process smoother. However, this paper about the fault tolerance of AMB power electronic devices only involves the open-circuit fault so far, it’s necessary to design a fault-tolerant control strategy for short-circuit fault.

Fig.1 shows the short-circuit fault-tolerant driving system in this paper, where the thrust AMB is driven by two H half-bridge topologies and two radial AMBs are driven by tow shared-bridge topologies. The shared-bridge topology consists of one bipolar bridge and four unipolar bridges under the normal working condition, each unipolar bridge is connected to one end of the coils and the other ends are connected to the bipolar bridge. It is well known that the electromagnetic force acting on a single degree-of-freedom(DOF) is the difference of the forces generated by two electromagnetic coils, referred to as A coil and C coil. So in order to achieve the short-circuit fault-tolerant control, one shared-bridge topology controls the A coils(x_{a1}, y_{a2}, x_{a3}, y_{a4}) and the other one controls the C coils(x_{c1}, y_{c2}, x_{c3}, y_{c4}). Then if the unipolar bridges are replaced by bipolar ones, the topology can both deal with open circuit and short circuit fault. Open-circuit fault tolerance can refer to reference [8], only short-circuit fault is considered in this paper. Fig.2 shows the core idea of short-circuit tolerance, when the short-circuit fault occurred to the top IGBT of bridge L_{a1}, driven topology will be rapidly switched from the normal mode to the fault-tolerant mode, where the bridge L_{a2} reverses, it doesn’t matter that the winding current i_{a2} is reversed, because the electromagnetic force of AMB is independent of winding current direction.

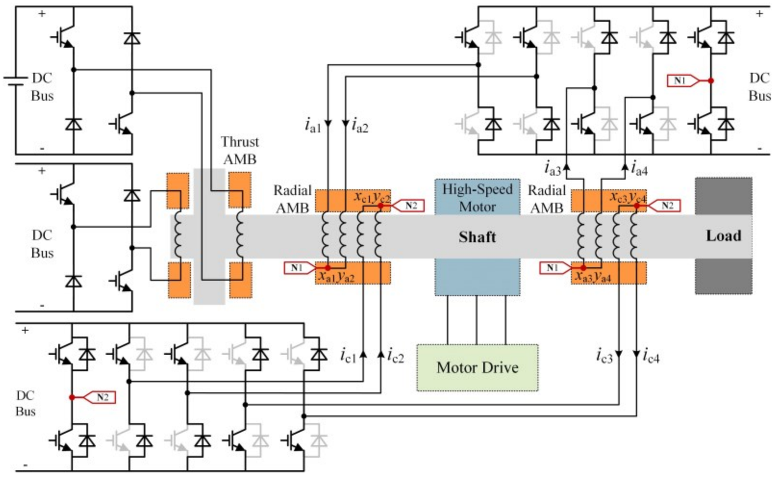


Figure 1 The short-circuit fault-tolerant drive system of AMB based on shared-bridge topology

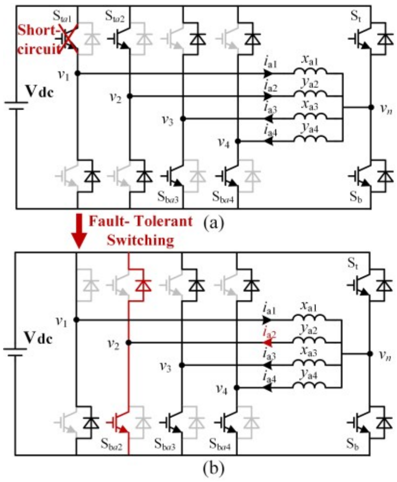


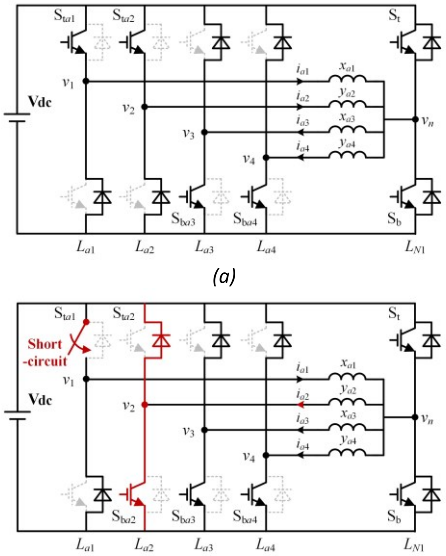
Figure 2 The fault-tolerant topology switching. (a): normal mode; (b): fault-tolerant mode

2. Fault-tolerant control strategy

2.1 Topology analysis in normal and fault mode

As shown in the Fig.3(a), the power electronic devices drawn with dotted lines are not working in normal mode. One end of coils are connected to four unipolar bridges separately and the other ends are connected the bipolar bridge together. Fig.4(a) shows the current control block diagram of shared-bridge topology in normal mode, the duty cycles of IGBTs on bridge L_{N1} are fixed at 0.5 and each control current(i_{a1}, i_{a2}, i_{a3}, i_{a4}) is decoupled. When the IGBT S_{ta1} occurs the short-circuit fault as shown in the Fig.3(b), the current i_{a1} will rise quickly and significantly deviate from the reference value since the midpoint voltage v_n of the bridge L_{N1} is fixed to $0.5v_{dc}$. If the control method is not changed at this time, the current control will fail, the rotor falls, and cannot work normally.

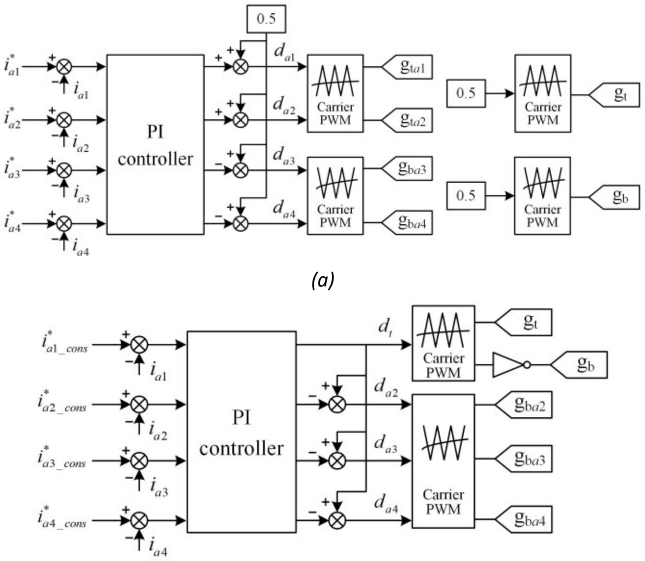
As shown in the Fig.4(b), in order to avoid the continuous rise of the current i_{a1}, the duty cycles of IGBTs on bridge L_{N1} are no longer fixed, but determined by the output of the PI controller (i_{a1}). The gate drive signal g_t needs to stay high level for a long time during a switching period to ensure that i_{a1} is controllable, which is exactly why the bridge L_{a2} needs to reverse, because it can greatly lower the impact of gate drive signal g_t on the wingding current i_{a2}. Although the above operations can ensure that each current is controllable, it will deteriorate the dynamic control performance of current. Therefore, the other core idea of the short-circuit fault-tolerant strategy is that the shared-bridge topology in which a short circuit occurred only generates the constant current, and the normal shared-bridge topology generates both bias current and control current.



(a)

(b)

Figure 3 The power amplifier drive topology. (a): normal mode; (b): fault-tolerant mode



(a)

(b)

Figure 4 Control block diagram of current loop. (a): normal mode; (b): fault-tolerant mode

2.2 Fault analysis and detection

The duty cycles of IGBTs on bridge L_{N1} are fixed at 0.5 in the normal mode, so when the short-circuit fault occurred to the top IGBT of bridge L_{a1}, the winding current i_{a1} will rise rapidly, however, the winding current i_{c1} that controls the same axis doesn't change suddenly due to it is controlled by the other shared-bridge topology, mostly, the sum of i_a and i_c is constant in normal operation. Therefore, the sum of i_a and i_c can be used to identify whether a short circuit fault has occurred, and the location of the fault can be distinguished by the rise rate of the current.

2.3 Fault-tolerant control system

Fig.(5) shows the short-circuit fault-tolerant control system, the difference of this from a normal AMB control system is the inclusion of a fault detection module and a fault-tolerant current controller. When the fault detection module detects a short-circuit fault, the current controller switches from normal mode to fault-tolerant mode, thus achieving fault-tolerant control of the AMB.

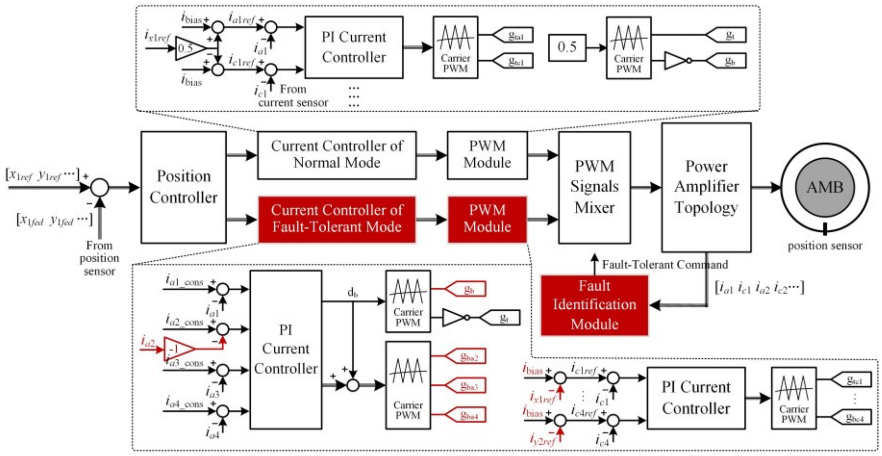


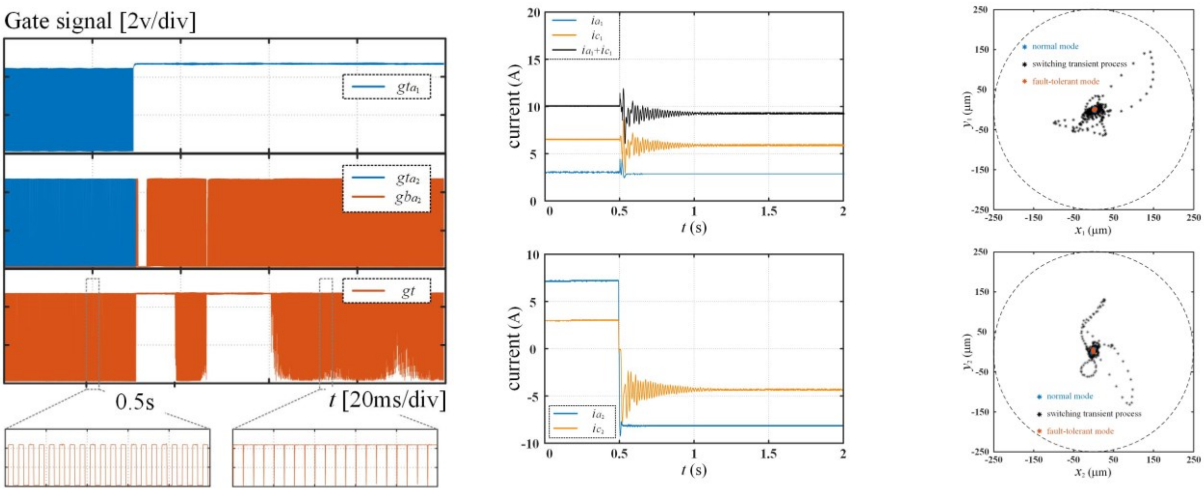
Figure 5 The short-circuit fault-tolerant control system diagram

Table 1 Main experimental parameters

Symbol	*Variable*	*Value*
Touch down bearing gap	g_0	250μm
AMB gap	s_0	500μm
DC voltge	V_{dc}	150V
Bias current	I_{bias}	5A
Switching frequency	f_s	20kHz
Rotor mass	m	5Kg
Coil inductance	L	14mh
Coil resistance	R	0.5Ω
The threshold value	I_{limit1}	11A
The threshold value	I_{limit2}	$V_{dc}/2L$

3. Experimental results

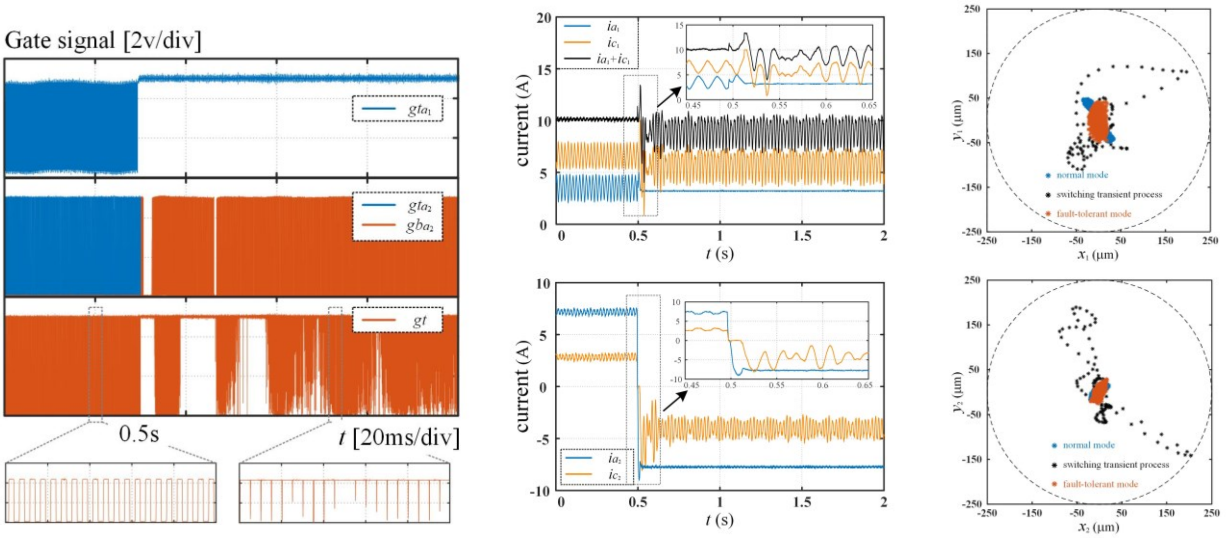
Experiments have been done to validate the effect of the short-circuit fault-tolerant control system, and the main parameters are listed in Table 1. Fig 6 shows the AMB fault-tolerant experimental results under static suspension after short-circuit failure of S_{ta1}, at 0.5s, the g_{ta1} is set to a constant high level to simulate the short-circuit fault of IGBT. It can be found the winding current i_{a1} starts to rise, when the sum of i_{a1} and i_{c1} is larger than i_{limit1} and the rise rate of i_{a1} is larger than i_{limit2}, the fault identification module identifies that fault, then sends a signal to switch the topology and change the mode of current controller. Fig.6 (a) and (b) indicates that after the short-circuit fault, the g_{ta2} is set to a constant low level, the bottom IGBT of L_{a2} starts to work, and the i_{a2} begins to flow in reverse. It can be also found that the winding current of the faulty shared-topology are controlled to a constant current, and the normal shared-bridge topology generates both bias current and control current like i_{c1}. Finally, fig.6 (c) shows that the rotor position returns to stable suspension after a transient fluctuation.



(a) *(b)* *(c)*

Figure 6 The short-circuit fault-tolerant experimental results under static suspension. (a): gate drive signals; (b): coil currents; (c): rotor *displacements*

Fig 7 shows the AMB fault-tolerant experimental results under rotor rotation after short-circuit failure of S_{ta1}, at 0.5s, the g_{ta1} is set to a constant high level to simulate the short-circuit fault of IGBT, and the relevant experimental results are basically consistent with the Fig.6.



(a) *(b)* *(c)*

Figure 7 The short-circuit fault-tolerant experimental results under rotor rotation. (a): gate drive signals; (b): coil currents; (c): rotor displacements

4. Conclusion

This paper proposes a short-circuit fault-tolerant strategy for AMB power electronic controller based on shared-bridge topology, which is compatible with fault tolerance of open-circuit fault. By the way, the variable bias current control after short circuit is worth further study.

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