Fault tolerant control for open winding brushless DC motor with power device failure

Huang Qi[1], Zhang Xianting[1], Xue Likun[1], Luo Ling[1], and Ma Ruiqing[1]

[1]Northwestern Polytechnical University

February 17, 2023

Abstract

Brushless DC motor (BLDCM) is widely used in aerospace equipment. But the neuter port in conventional BLDCM windings could lead to torque ripples and low reliability. Each phase winding of the open winding BLDC is connected to an H-bridge inverter, and its phase voltage and phase current could be controlled independently, which has a certain fault tolerance. Firstly, the circuit topology and conduction mode of the open-winding brushless DC motor are introduced, and a Matlab simulation model is established according to the mathematical equation of the motor. Then, the operation characteristics of the open winding brushless DC motor with power device failure are analyzed, and the characteristics of two fault-tolerant control methods, compensation and reconstruction, are discussed. Finally, the open winding brushless DC motor and controller are processed, and the experimental platform is built to verify the operation characteristics of the open winding brushless DC motor with normal operation and compensation operation.

Fault tolerant control for open winding brushless DC motor with power device failure

Huang Qi [1,2],*Zhang Xianting*[1,3],*Xue Likun*[1,3], *Luo Ling* [1],*Ma Ruiqing* [1]

1. Northwestern Polytechnical University,Xi'an Shanxi 710072;

2. Guizhou University,Guiyang Guizhou 550081,

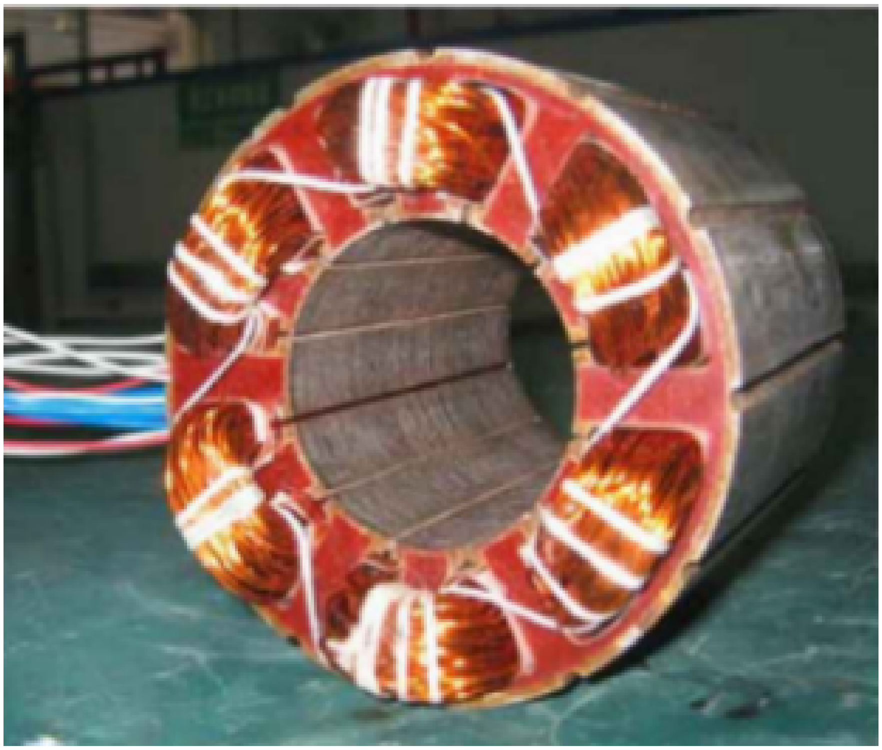
3. Guizhou Aerospace Linquan Motor Co., Ltd,Guiyang Guizhou 550081

Abstract: Brushless DC motor (BLDCM) is widely used in aerospace equipment. But the neuter port in conventional BLDCM windings could lead to torque ripples and low reliability. Each phase winding of the open winding BLDC is connected to an H-bridge inverter, and its phase voltage and phase current could be controlled independently, which has a certain fault tolerance. Firstly, the circuit topology and conduction mode of the open-winding brushless DC motor are introduced, and a Matlab simulation model is established according to the mathematical equation of the motor. Then, the operation characteristics of the open winding brushless DC motor with power device failure are analyzed, and the characteristics of two fault-tolerant control methods, compensation and reconstruction, are discussed. Finally, the open winding brushless DC motor and controller are processed, and the experimental platform is built to verify the operation characteristics of the open winding brushless DC motor with normal operation and compensation operation.**Key Words:** Open Winding;Brushless DC motor;Fault-tolerant control;Compensation; Reconstruction

1. Introduction

Brushless DC motor is composed of permanent magnet motor body, controller and position sensor. Brushless DC motor is widely used in automobiles, household appliances, robots, aerospace equipment and other fields due to its high power density, good speed regulation performance, long life, small size and light weight[1-2]. The stator winding of the traditional brushless DC motor usually adopts a star-connected structure, driven by a three-phase full-bridge inverter circuit[3]. Due to the public point of the three-phase winding, when a phase winding or its inverter circuit fails, it will affect the operation of other phase windings, resulting in the motor not running smoothly, or even burn out the winding, which cannot meet the high reliability requirements of the motor[4-5]. Redundant motors and fault-tolerant motors are usually used in the field of electric drive that requires high stability and high reliability. However, the structure of these two structural motors is very complex, requiring a large number of windings. The armature of the motor often adopts the concentrated winding structure of the slot placement, and the utilization rate of the winding is not high[6-7]. Meanwhile, the manufacturing process of the winding is complex, which leads to the increase of the volume and weight of the motor and the increased cost.

The open winding structure is to disconnect the neutral point between the motor windings, the structure of the stator and rotor does not change, and each phase winding is connected to its own drive circuit[8-10]. The voltage and current of each phase winding can be controlled separately, and there is electrical isolation between the phase windings. Although the power device of the open winding brushless DC motor controller is more than twice that of the traditional brushless DC motor controller, the withstand voltage of each device is only half of the DC bus voltage[11-12], so that the switching loss of the power device and the requirements of the radiator are reduced, and the overall cost and use space of the motor controller do not change much, which is suitable for high reliability, high voltage and high power driving occasions. Although the open winding motor inverter and three level inverter can achieve three-level voltage output effect, the open winding motor controller does not need clamping diodes and does not have the problem of capacitor midpoint voltage drift, which is more reliable than three-level converter[12]. At present, the open winding structure has been applied to permanent magnet motor, assynchronous motor, generator, transformer and other electrical [13-15]. Compared with fault-tolerant motor, open winding brushless DC motor can use fractional slot windings to reduce torque ripple, use double-layer winding to improve the winding utilization and reduce the current harmonics[16], as shown in Figure 1. Although there is still a magnetic circuit coupling between the adjacent windings in open winding brushless DC motor, the electrical isolation between the windings has been realized, with good fault-tolerant performance. The fixed rotor magnetic circuit of the brushless DC motor has not changed, and the original motor production process can be extended, which is convenient to realize in engineering.



(a) Fault tolerant motor (b) Open winding brushless DC motor

Fig.1 Stator and winding structures

Similar to traditional permanent magnet brushless motors, open-winding brushless DC motors also have two control methods: square wave control and sine wave control. Domestic and foreign scholars have done a lot of research on open-winding brushless DC motor with sine wave control method, including improving efficiency, improving voltage utilization rate, reducing common mode voltage, etc[17-19]. However, the sine wave control method requires high-precision position sensor (rotary transformer or photoelectric encoder) to obtain the rotor position angle, and requires high-performance chip for coordinate transformation and SVPWM operation, resulting in high system cost. The brushless DC motor with square wave control method only needs three Hall position sensors and commutation logic circuit, the system cost is low and the control algorithm is simple.

This paper first introduces the circuit topology and conduction mode of the open winding brushless DC motor, and establishes the Matlab simulation model according to the mathematical equation of the motor. Then the power device fault of the open-winding brushless DC motor is analyzed, and the fuse is used as the protection device for the power device fault. Simulation method is used to analyze the effect of the two fault tolerance methods: compensation method and reconstruction method. Finally, a prototype experiment platform is built to verify the effect of the compensation method with power device failure.

2 Topology and conduction mode

2.1 Circuit topology

Each phase winding of open-winding brushless DC motor is connected with an independent H-bridge inverter circuit[20]. Considering the cost and environmental adaptability, the three H-bridge inverter circuits of three-phase winding are powered by the same DC power supply. The open winding brushless DC motor inverter circuit contains 12 power devices, as shown in Figure 2, V1i (i=1~4) is the 4 power devices connected by the A-phase winding, U0 is the DC power bus voltage, and I0 is the power bus current. Although the number of power devices in the open winding brushless DC motor controller is twice that of the conventional brushless DC motor controller, the withstand voltage resistance of each power device is reduced by half.

Fig.2. Circuit topology of the open windings brushless motor controller

2.2 Conduction mode

Each phase winding of open winding brushless DC motor has three states, positive conduction, off and negative conduction. At any time of motor operation, the three-phase winding can be one-phase winding conduction, two-phase winding conduction or three-phase winding conduction. The armature magnetomotive force generated by three-phase winding is shown in Figure 3, is the magnetomotive force when the winding of each phase is in positive conduction. is the magnetomotive force when the winding of each phase is in negative conduction. is the composite magnetomotive force when the two phase windings are energized at the same time, in which one winding is in the positive conduction and the other winding is in negative conduction. is the composite magnetomotive force when the three phase windings are energized at the same time, in which one winding is in the positive conduction and the other two winding are in negative conduction, or one winding is in the negative conduction and the other two windings are in positive conduction.

Fig.3. Magnetomotive force

According to the operation principle of brushless DC motor, the stator armature winding generates jumping rotating magnetomotive force in space. The traditional brushless DC motor usually adopts two-phase conduction with six states mode. There are eight conduction modes of open winding brushless DC motor, among which there are three modes when the winding is energized in the one-way, and there are five modes when the winding is energized in both forward and revers[21]. The waves of winding current and back electromagnetic force(EMF) in eight conduction modes are shown in FIG. 4.

(1) Unidirectional& single-phase conduction with three states mode: only one phase winding is energized in each state, and each phase winding is energized in unidirectional direction with 120° electrical angle. Suppose a commutation period is 360° electrical angle, the same as below.

(2) Unidirectional& alternating between single-phase conduction and two-phase conduction with six states mode: each phase winding is energized in unidirectional direction with 180° electrical angle.

(3) Unidirectional& two-phase conduction with three states mode: each phase winding is energized in unidirectional direction with 240° electrical angle.

(4) Bidirectional& single-phase conduction with six states mode: only one phase winding is energized in each state, and each phase winding is positively energized with 60° electrical angle, disconnected with 120° electrical angle, and then negative energized with 60° electrical angle, disconnected with 120° electrical angle.

(5) Bidirectional& alternating between single-phase conduction and two-phase conduction with twelve states mode: each phase winding is positively energized with 90° electrical angle, disconnected with 90° electrical angle, and then negative energized with 90° electrical angle, disconnected with 90° electrical angle.

(6) Bidirectional& two-phase conduction with six states mode: each phase winding is positively energized with 120° electrical angle, disconnected with 60° electrical angle, and then negative energized with 120° electrical angle, disconnected with 60° electrical angle.

(7) Bidirectional& alternating between two-phase conduction and three-phase conduction with three states mode: each phase winding is positively energized with 150° electrical angle, disconnected with 30° electrical angle, and then negative energized with 150° electrical angle, disconnected with 30° electrical angle.

(8) Bidirectional& three-phase conduction with six states mode: each phase winding is positively energized with 180° electrical angle, and then negative energized with 180° electrical angle.

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Fig.4 Conduction models of open winding Brushless DC motor

3 Simulation model

3.1 Mathematical equation

Each phase winding of open winding brushless DC motor is independent of each other, and the voltage balance equation of each phase winding is as follows:

(1)

Where 、 、 、 (x=a、b、c) are the winding phase current, back electromotive force(EMF), resistance and inductance, respectively. is the DC power voltage, is the voltage drop on the power device.

The back electromotive force waveform of open winding brushless DC motor is the same as that of conventional brushless DC motor. The back electromotive force waveform is a trapezoidal wave with a flat top width of 120 ° (electrical angle), the amplitude calculation formula of trapezoidal wave is

(2)

Where is air gap flux, is the back potential constant,n is the motor speed.

When the motor is running in steady state, =0,the phase current of the winding is:

(3)

The calculation formula of electromagnetic power and torque of motor is as follows:

(4)

(5)

When ω is the motor electrical speed.

The relationship among electromagnetic torque, load torque and speed of open winding brushless DC motor is shown as follows

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(6)

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Where, is the load torque, is the friction coefficient, and is the moment of inertia of the rotor.

3.2 Matlab model

There are three common methods for motor modeling: mathematical interpretation, digital modeling and finite element modeling. Mathematical interpretation method builds the model according to the electromagnetic transient equation of the motor, and the accuracy of the model depends on the electromagnetic parameters[22]. Digital modeling is usually realized by using Matlab Simulink tool software, the model is connected by various electrical modules which assumed to work in an ideal state[23]. It is difficult for digital modeling to simulate the running state of the actual circuit in complex working conditions, but it can simulate the influence trend of parameters on the model. Finite element model can comprehensively consider electrical, magnetic, thermal and other factors, but the model is complex and needs to be configured with many empirical parameters. This paper uses Matlab Simulink tool software to model open winding brushless DC motor. The model is composed of DC power supply, H-bridge inverter, load, commutation module, motor sub-model, oscilloscope, etc., as shown in Figure 5, the details of the model is described as follows.

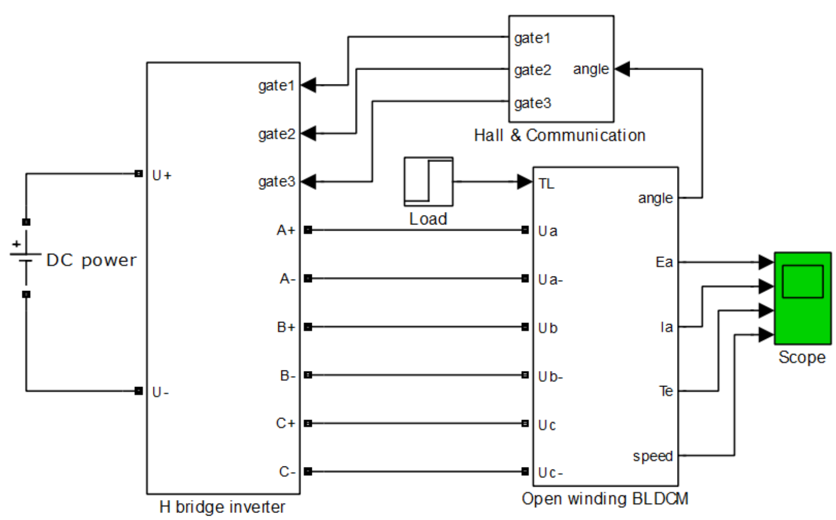

Fig.5 Matlab Simulink model

(1) Voltage balance equation module of motor

According to formula (1), the phase winding voltage balance equation model of open winding brushless DC motor is established, as shown in Figure 6.

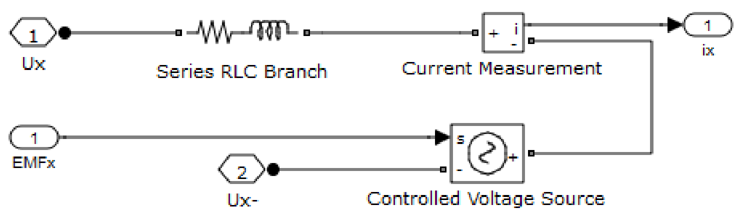

Fig.6 Voltage balance equation

(2) Back electromotive force module

The value of the back electromotive force is related to the rotor position angle. The back electromotive force module can be established by Simulink table (Lookup Table) module. The back electromotive force of three phase windings are ideal trapezoidal wave with a 120° electric angle, and the instantaneous value of the back electromotive force of each phase winding is calculated according to the running angle of the rotor, as shown in Figure 7.

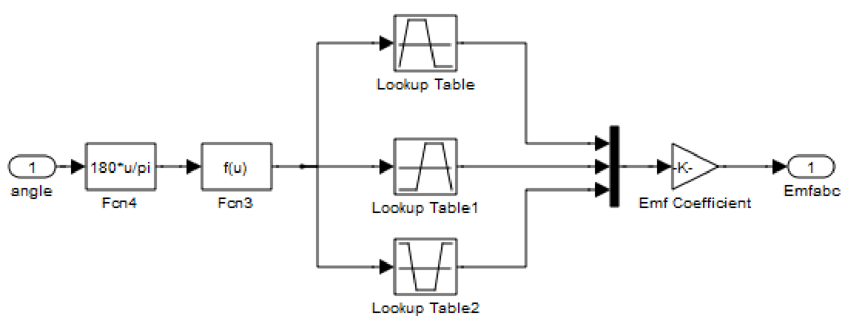

Fig. 7 Back electromotive force module

(3) Torque module

The torque module is established according to the electromagnetic torque equation (5), as shown in Figure 8.

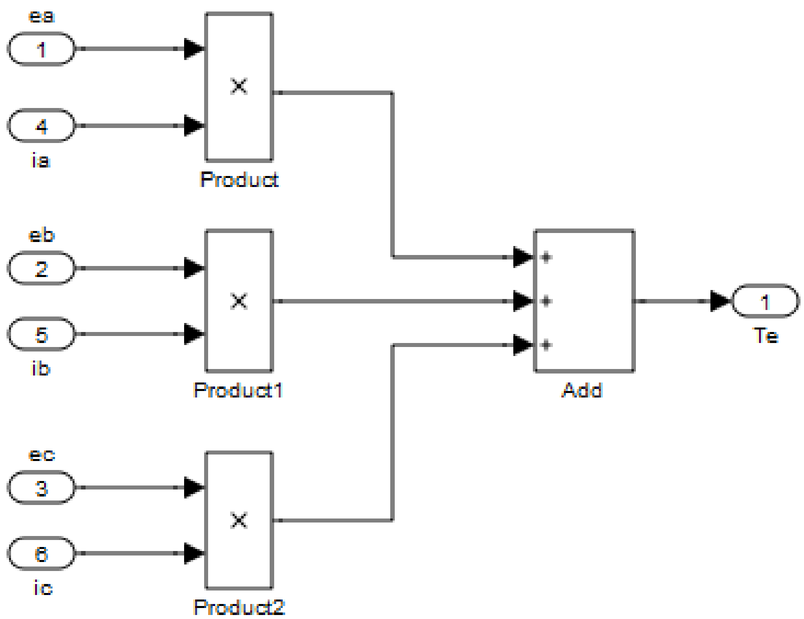

Fig.8 Torque model

(4) Equation of motion module

Figure 9 shows the equation of motion module of the motor. Integrating the difference between the electromagnetic torque and the load torque yields the rotating mechanical angular velocity of the motor. Integrating the angular velocity gets the angle of the motor, then multiply the number of poles to obtain the electric angle of the motor.

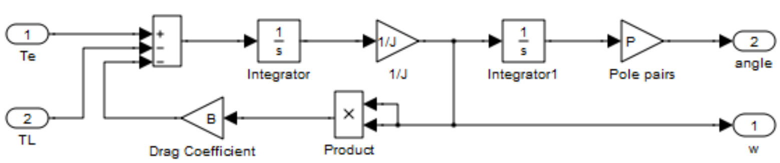

Fig.9 Equation of motion module

(5) Three H-bridge inverters module

The drive circuit of open winding brushless DC motor consists of three H-bridge inverters. Each H-bridge inverter consists of 4 power devices. The H-bridge inverter can be modeled using the Universal Bridge module provided by the SimPowerSystem toolbox of Simulink, as shown in Figure 9:

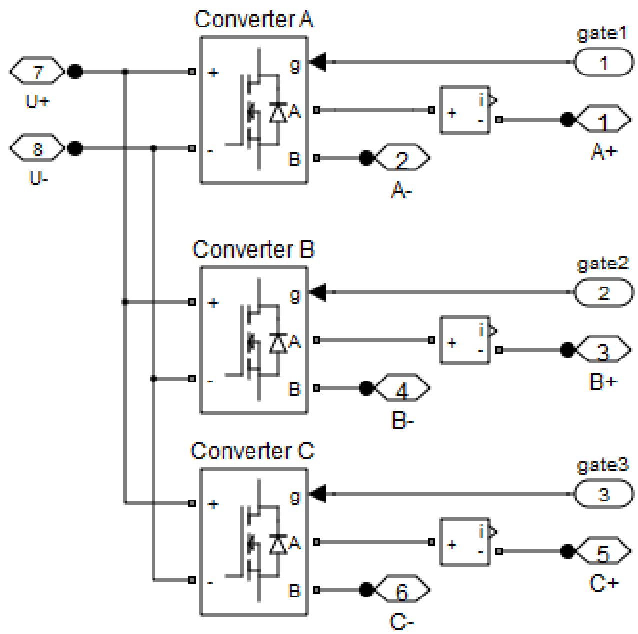

Fig. 10 Three H-bridge inverters module

(6) Commutation control module

The commutation control module can also be established by Simulink table (Lookup Table) module. According to the rotor position angle, the switching signal of the power device is obtained. The two switches at the diagonal of each H-bridge inverter driver are turned on and cut off at the same time.

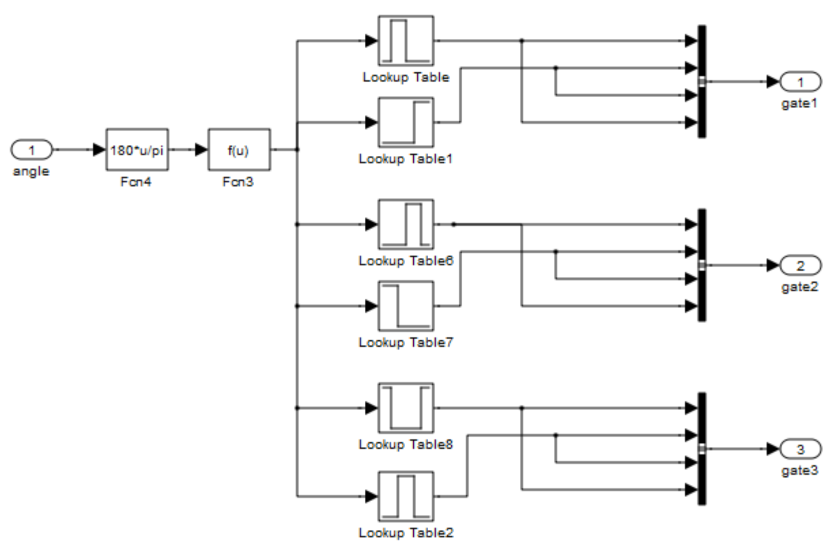

Fig. 11 Commutation control

The parameters of the open winding brushless DC motor are shown in Table 1.

Table 1. Motor parameters

Name	Value	Unit
Rated Power	10	W
Rated Voltage	28	V
Rated Speed	750	r/min
Rated Torque	0.13	Nm
Number of Poles	4	
Phase Resistance	5.1	Ω
Phase Inductance	5.4	mH
Rotor inertia	$0.\ 97\times10^{-4}$	$4J/kg*m^2$
Back EMF coefficient	0.3	$V/rad*s^{-1}$

3.3 Simulation of two-phase conduction with six states mode

Three phase brushless DC motor usually adopts two-phase conduction with six states mode, as shown in Figure 12. The 360 ° electrical angle cycle is divided into 6 equal states, and the rotor rotates 60 ° electrical angle in each state while two phase of winding are powered on. One phase is positively energized and the other phase is negative energized.

Fig. 12 two-phase conduction with six states mode

The simulation waveforms of phase current ia, ib, ic, torque T and speed n of open winding brushless DC motor with no-load and rated load are shown in Figure 13. The motor starts with no load, the speed of motor with no-load is about 900r/min, and the phase current of motor with no-load is about 0.05A. At 0.15ms, the rated load torque of 0.13Nm is applied to the motor. The speed of motor with rated load is about 750r/min, and the phase current of motor with rated load is about 0.45A. The maximum torque fluctuation is about 25%, the maximum starting current is about 2 times the rated load current.

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Fig. 13 Simulation waveforms under normal operation

4 Power device fault analysis

The faults of open winding brushless DC motor system mainly include motor body fault, controller fault and sensor fault,such as open-winding, short circuit of phase winding, short circuit between turns, permanent magnet demagnetization, bearing damage, rotor sweeping, position sensor failure, short circuit of power device, open circuit of power device, power supply failure, control chip fault, drive chip fault, voltage/current sensor fault, etc[25-26]. Power devices operating at very high switching frequencies have the greatest probability of failure due to the large du/dt and di/dt shocks.

4.1 Fault prevention method

In practical application, the motor does not allow to stop suddenly or for a long time. Even if there is a fault, it is necessary ensure that the motor can continue to operate without reducing or reducing the performance of part of the motor, so as to minimize the economic loss caused by the fault. There are three types of fault prevention methods: hardware protection, regular patrol inspection and online diagnosis.

(a) Hardware protection

Many motor controllers are equipped with hardware protection devices. Due to the fuse, air open circuit breaker, hardware overvoltage / current protection circuit, they can realize the protection functions, such as over current protection, over voltage protection, undervoltage protection, overheating protection, grounding protection, vibration over-limit protection, overspeed protection, etc[27]. When the motor operation parameters and state parameters reach or exceed the set value of the controller, the motor controller will alarm with reducing the power operation or stopping processing, to prevent the over-limit operation from damaging the motor. This method has fast response speed wtih less equipment investment, which is widely used in motor protection systems.

(b) Regular patrol inspection

Regular patrol inspection is usually used to prevent the occurrence of faults in some key application areas which the motor is not allowed to operate under shutdown and fault. Operators use some special detection equipment (such as insulation tester, spectrum analyzer, thermal imager, etc.) to regularly detect the motor system, then replace or maintain the motor parts that may fail in advance[28-29]. This method is widely used in the field of life and production security, and requires fixed manpower and equipment.

(c) Online diagnosis

Through the reasonable application of online state detection and fault diagnosis technology, the actual state of the equipment can be effectively understood and mastered, so as to evaluate and predict the reliability of the equipment[30]. The motor controller in closed-loop control applications needs to compare the set value of the target with the voltage, current and speed signals detected by sensors, which can be used as input data for online diagnosis. Online diagnosis can make use of the existing detection data to predict the state in most cases. This method only increases some function in the program without increase the hardware cost, which has been applied in various electronic products. There is also a risk of processing delays when the logic of online detection is very complex.

With the application of various detection sensors and protection algorithms, the controller can detect the overtemperature, overcurrent and open circuit equality in the process of motor operation in time, then stop motor or reduce the operation power of motor, so it can greatly reduce the probability of motor failure and sensor failure. However, it is difficult for the controller to detect the power device fault in time when it occurs under overvoltage, surge current, static electricity, bad welding and other conditions, which may lead to motor system fluctuation, insulation damage, winding overheating and burning, etc. Therefore, it is necessary to analyze the fault characteristics of the power device so that the controller can deal with it in time.

4.2 Fault analysis for short circuit of power device

The inverter circuit of A-phase winding is selected to analyze the short circuit fault of power device in open winding brushless DC motor controller. All four power devices V11˜V14 may have an open circuit failure, possibly in one or more power devices. Short circuit of power device is a major fault of the motor inverter. As long as there is one power device with short circuit in H-bridge inverter, the positive and negative of DC power supply will be short-circuited when the power device connected in series the power device with short circuit on the same bridge arm are turned on, resulting in the burning of the power devices connected in series due to the excessive current. Therefore, the power device connected in series the power device with short circuit on the same bridge arm must not be turned on. At this time, the winding connected to the H-bridge inverter can only be unidirectional energized, as shown in Figure 14 (a).

There are some different situations in the H-bridge inverter when two power devices are short-circuited. When the two short-circuited power devices are located at the upper or at the lower bridge arm, or at one side of the bridge arm at the same time, as shown in Figure 14 (b) - (c), once the switch is turn on, the DC power supply will be short-circuited. When the two short-circuited power devices are located at the opposite corner of bridge arm, as shown in Figure 14 (d), the phase winding will be unidirectional energized forever and never be turned off .

In order to prevent various hazards caused caused by short circuit of power device, a fuse or protective relay is usually connected in series on the positive pole of the DC power supply of the H-bridge inverter circuit to cut off the fault module in time. The fault module can also be cut off by judging whether the bus current exceeds the limit online. But this method is not as effective as the fuse or protective relay. If the control chip is disturbed or other faults occur at the same time, the failure handling measures cannot be taken effectively. On the other hand, the treatment measures delay may be occurred the control chip, which can not minimize the hazards.

One power device with short circuit

(b) Two power devices with short circuit at one side of the bridge arm

(c) Two power devices with short circuit at the upper or at the lower bridge arm

(d) Two power devices with short circuit at the opposite corner of bridge arm

Fig. 14 Type of short circuit of power device

4.3 Fault analysis for open circuit of power device

Obviously, as long as there are three or four power devices with open circuit in H-bridge inverter, the phase winding can not be energized. When one or two power devices of the H-bridge inverter have an open circuit fault, the winding may also be energized. When the H-bridge inverter circuit with only one open-circuited power device, the phase winding can be unidirectional energized, as shown in Figure 15 (a).When the two open-circuited power devices are located at the upper or at the lower bridge arms, or at one side of the bridge arm at the same time, as shown in Figure 15 (b) - (c), the winding cannot be energized. When the two open-circuited power devices are located at the opposite corner, as shown in Figure 15 (d), the phase winding can be unidirectional energized

(a) One power device with open circuit

(b) Two power devices with open circuit at one side of the bridge arm

(c) Two power devices with open circuit at the upper or at the lower bridge arm

(d) Two power devices with open circuit at the opposite corner of bridge arm

(e) Three power devices with open circuit

Fig. 15 Type of open circuit of power device

5 Fault tolerant control

According to the above analysis, most power device failures of open winding brushless DC motor system are treated as unidirectional energized fault or open circuit fault of phase winding. When a phase winding is removed or a phase winding can only be energized in single direction, the armature magnetomotive force is generated by current of the remaining phase winding. The motor can continue to run when the remaining magnetic field vector of the armature is controlled to rotate in a certain order. But the electromagnetic torque ripple of the motor increases at this time, bringing vibration and noise. There are two fault tolerant control methods for brushless DC motor system with open winding: compensation method and reconstruction method.

5.1 Compensation method

Compensation method is that cutting off the faulty winding of the motor and increasing the current of the remaining phase winding so that the input electric energy of the motor remains unchanged[31].

(a) Unidirectional energized fault of phase winding

The fault phase winding unidirectional energized can only generate a armature magnetomotive force in one direction. Assuming phase winding A is unidirectional energized, the magnetomotive forces of each phase winding are shown in Figure 16(a). The composite magnetomotive forces generated by three-phase winding are shown in Figure 17(a), among them, four armature magnetomotive forces are synthetic vectors and two armature magnetomotive forces are individual vectors. As can be seen from the figure, the spatial arrangement of the six armature magnetomotive forces deviates from the regular hexagon shape, resulting in the reduction of effective output power of the motor and the increase of torque ripple.

(a) Unidirectional energized (b) Open circuit

Fig. 16 Magnetomotive force with fault

(a) Unidirectional energized (b) Open circuit

Fig.17. Compensation method

The input electric energy of open winding brushless DC motor with two-phase conduction with six states mode in a conduction cycle is:

(6)

Where P_A,P_B,P_C are the average power of three phase winding.

Because the motor is an inertial system, the speed will not suddenly change. Assuming that the amplitude of the back electromotive force(EMF) is constant in a conduction cycle, the input electric energy of the motor in a conduction cycle is:

(7)

Where T_0 is the duration of one conduction state.

When phase winding C is unidirectional energized, the input electric energy of open winding brushless DC motor in a conduction cycle is:

In order to keep the input electric energy of the motor in fault state equal to that in normal state, it is necessary to increase the winding current to 1.2 times.

The simulation waveforms of phase current ia, ib, ic, torque T and speed n of open-winding brushless DC motor when phase winding C is unidirectional energized are shown in Figure 18. The motor starts with no load, the speed of motor with no-load is about 860r/min. The rated load torque of 0.13Nm is applied to the motor at 0.15ms. The speed of motor with rated load is about 720r/min, and the phase current of motor with rated load is about 0.55A, which is about 1.2 times the normal operating current. The maximum torque fluctuation is about 45%.

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Fig. 18 Simulation waveforms under unidirectional energized fault

(b) Open circuit fault of phase winding

When the phase winding A has an open circuit fault, the phase winding A cannot generate a magnetomotive force, as shown in Figure 16 (b), The composite magnetomotive forces generated by the remaining two phase windings are shown in Figure 17(b), among them, two armature magnetomotive forces are synthetic vectors and four armature magnetomotive forces are individual vectors. As can be seen from the figure, the spatial arrangement of the six armature magnetomotive forces presents a diamond shape, resulting in the reduction of effective output power of the motor and the increase of torque ripple.

The input electric energy of open winding brushless DC motor in a conduction cycle when the phase winding C has an open circuit fault is:

In order to keep the input electric energy of the motor in fault state equal to that in normal state, it is necessary to increase the winding current to 1.5 times.

The simulation waveforms of phase current ia, ib, ic, torque T and speed n of open-winding brushless DC motor when the phase winding C has an open circuit fault are shown in Figure 19. The motor starts with no load, the speed of motor with no-load is about 820r/min. The rated load torque of 0.13Nm is applied to the motor at 0.15ms. The speed of motor with rated load is about 700r/min, and the phase current of motor with rated load is about 0.68A, which is about 1.5 times the normal operating current. The maximum torque fluctuation is about 60%.

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Fig. 19 Simulation waveforms under open circuit fault

5.2 Reconstruction method

Reconstruction method is that cutting off the faulty winding of the motor and adjusting the conduction mode of the remaining phase winding so that the stator armature winding generates jumping rotating magnetomotive force in space[32]. A conduction cycle includes six or three states, the amplitude of armature magnetomotive force in each state is constant, so that the torque ripple of the motor will not increase too much, but the output power of the motor will decrease. When the phase winding C has a fault, it is necessary to control the amplitude of the remaining winding voltage to generate six or three uniform magnetomotive force space vectors in a conduction cycle, as shown in Figure 16 (b). Voltage amplitude control can be realized by PWM modulation module of special chip or digital chip, but it will increase the system cost and the control algorithm is complex. So that reconstruction method is rarely applied in practice.

(a)Six states conduction mode(b)Three states conduction mode

Fig.20. Reconstruction method

6 Experimental analysis6.1 Prototype and test platform

Open winding brushless DC motor can be obtained by cutting the neutral point between the windings of the conventional brushless DC motor. The stator and rotor structure of open winding brushless DC motor is the same as that of traditional brushless DC motor, so the production process of traditional brushless DC motor can be extended.

The structure and function of the open winding brushless DC motor controller is the same as that of the traditional brushless DC motor controller, which is composed of the main control board, drive board and power board[33], as shown in Figure 21. Motor controller realizes winding commutation and speed calculation according to the signal of position sensor, and collects voltage and current signal to realize overvoltage/ undervoltage protection, overcurrent and locked-rotor protection. Main control board is responsible for data processing: detecting the rotor position signal current and voltage information, judging the state of the motor, and handling fault tolerance control or shutdown. Drive board is mainly used to isolate and amplify the control signals sent by main control board, at the same time isolate, regulate and transmit the bus voltage, phase current and rotor position signals of the motor to main control board. Power board of open winding brushless DC motor controller consists of three H-bridge inverters, while power board of traditional brushless DC motor controller is composed of a three-phase full-bridge inverter.

Fig. 21 Structure of motor controller

The test platform of open winding brushless DC motor is shown in Figure 22, the input end of the motor controller is connected with a DC power supply, three H-bridge inverter circuits of the motor controller are connected to three phase windings of the motor. The dynamometer applies load torque to the motor and collects the motor speed signal. The oscilloscope detects the phase current waveform of the motor through the current sensor.

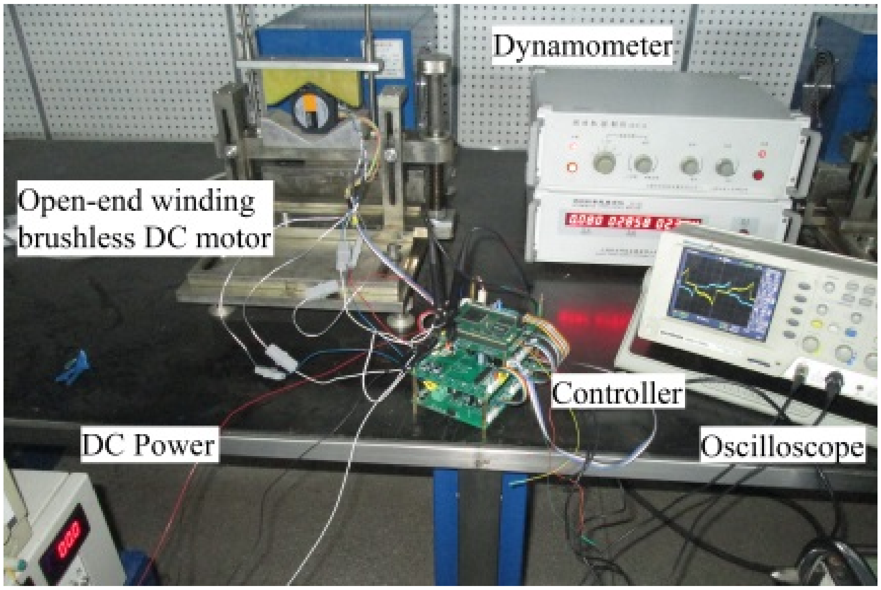
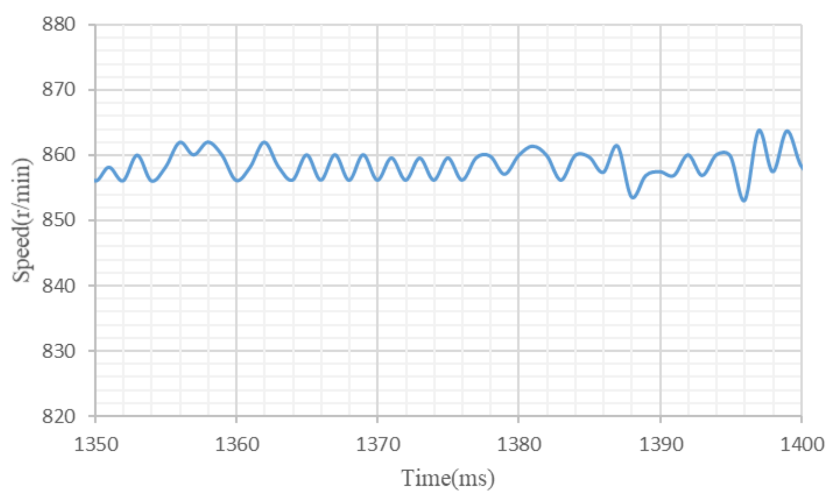


Fig. 22Test platform

6.2 Compensation method test

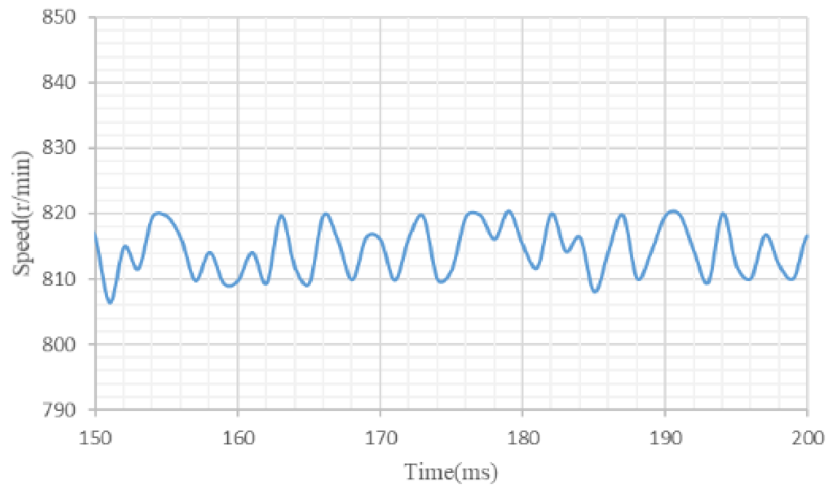
Because the motor is vulnerable to other damages during fault operation and the fault transient process is difficult to detect, the low load state (0.05Nm, 860r/min) is selected during the test, the speed fluctuation range is within 10 rpm, and the phase current is about 0.2A, as shown in Figure 17(a). When phase winding C is unidirectional energized, the current of the remaining phase winding is about 0.24A, which is 1.2 times of the normal current, the motor speed is about 810r/min, and the speed fluctuation range is within 15 rpm, as shown in Figure 17 (c)-(d). When the phase winding C has an open circuit fault, the current of the remaining phase winding is about 0.29A, which is 1.5 times of the normal current, the motor speed is about 810r/min, and the speed fluctuation range is within 20 rpm, as shown in Figure 17 (e)-(f). Although the output power of the motor is reduced, the motor can still operate continuously and has a certain fault-tolerant ability, which verifies the simulation results in Chapter 5.1.

(a) Current waveform under normal operation



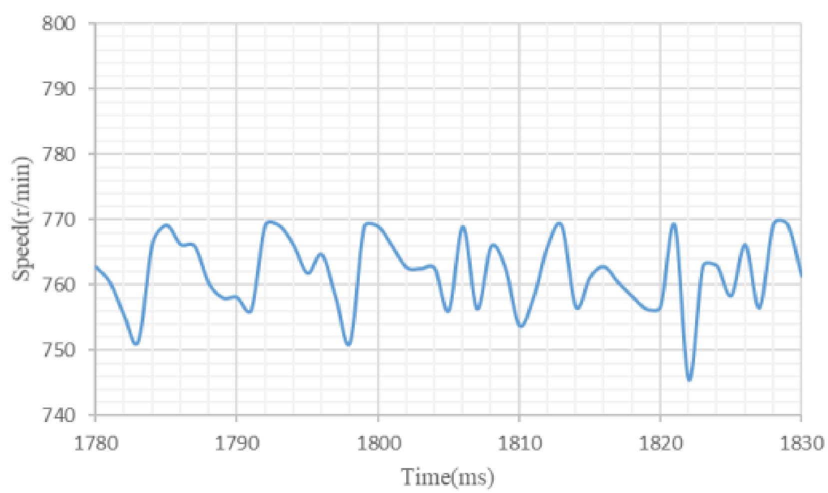
(b) Speed waveform under normal operation

(c)Current waveform under unidirectional energized fault



(d)Speed waveform under unidirectional energized fault

(e)Current waveform under open circuit fault



(f)Speed waveform under open circuit fault

Fig. 23 Test waveform

7 Conclusion

Three phase windings of open winding brushless DC motor are driven by three independent H-bridge inverters, and there is no neutral point between three phase windings, therefore open winding brushless DC motor has certain fault-tolerant characteristics. The stator and rotor structure of open winding brushless DC motor is the same as that of traditional brushless DC motor, so the production process of traditional brushless DC motor can be extended. Although the power device of the open winding brushless DC motor controller is more than twice that of the traditional brushless DC motor controller, the withstand voltage of each device is only half of the DC bus voltage. Power devices operating at very high switching frequencies have the greatest probability of failure due to the large du/dt and di/dt shocks. Hardware protection the most effective fault prevention measure, which can cut off the fault components of motor system in time. There are two common methods of fault-tolerant control: reconfiguration method will increase the system cost and the control algorithm is complex, compensation method will increase the current of the remaining phase winding and reduce the output power of the motor, but this method is simple and feasible.

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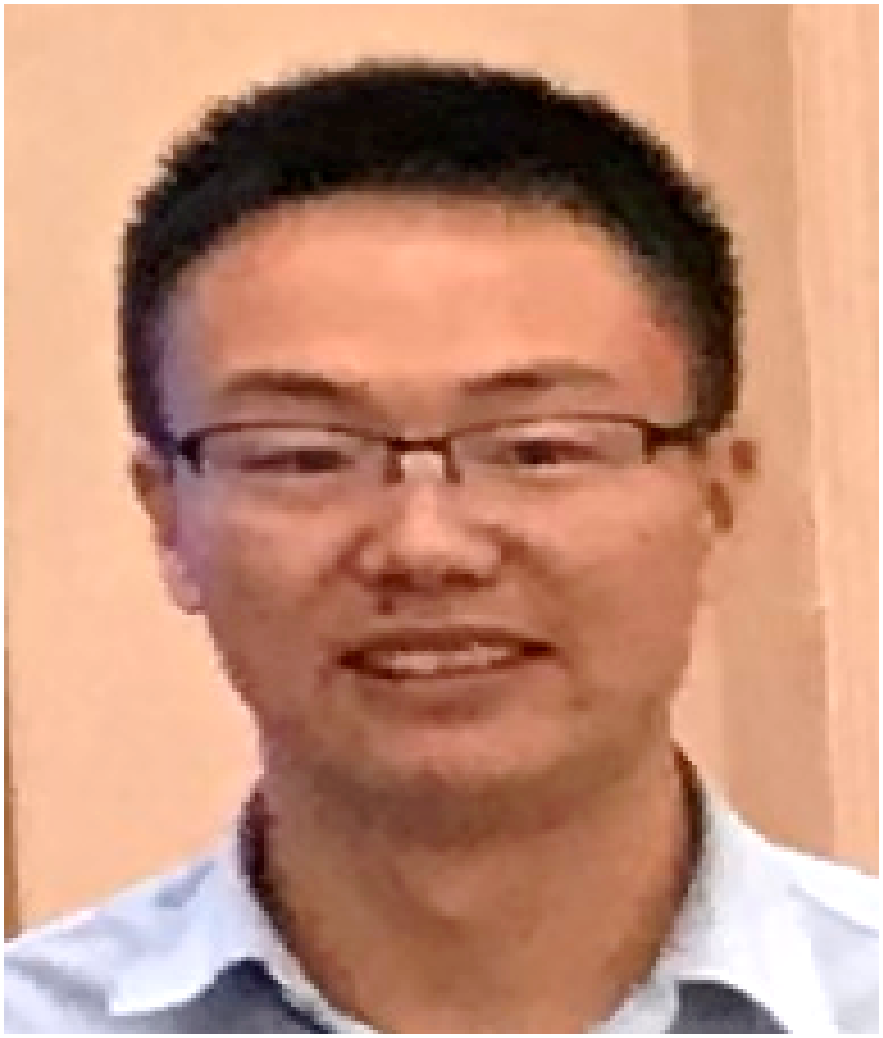
Biographies

Huang Qi was born in Hengyang, Hunan Province, China, in 1986. He received his M.S. and Ph.D. degrees in Electrical Engineering from Northwestern Polytechnical University, Xi'an, China, in 2012 and 2018, respectively. He has been a Postdoctoral Researcher in the Key Laboratory of Small & Special Motor and Drive Technology, Guiyang, China. His current research interests include magnetic levitation technology, high speed motor design, electric vehicles, and vibrating suction methods.

Zhang Xianting was born in 1982. He received the M.Sc degrees in electrical engineering from Guizhou University. Guiyang, China, in 2012. He is currently pursuing the Ph.D. degree with Mechanical Engineering in Northwestern Polytechnical. His current research interests include high speed motor design, simulation analysis and testing.



Xue Likun was born in 1993. He received the M.Sc degrees in electrical engineering from from Northwestern Polytechnical University, Xi'an, China, in 2017. he is currently pursuing the Ph.D. degree in electrical engineering. His current research interests include the design of the high-speed electrical machine and the coupling analysis of multiphysics in the permanent magnet electrical machine.

LuoLing was born in 1970. She received the Ph.D. degree in electrical engineering from Northwestern Polytechnical University, Xi'an, China, in 2004. She is currently a professor in Key Laboratory of Micro Motors and Drive Technology in Shaanxi Provincial. Her current research interests include special motor design, simulation and testing..

MaRuiqing received the B.S., M.S., and Ph.D. degrees from Northwestern Polytechnical University, Xi'an, China, in 1985, 1988, and 2007, respectively, all in electrical engineering. He is currently a Professor of electrical engineering and an Associate Director of the Institute of REPM Electrical Machines and Control Technology, Northwestern Polytechnical University. His research interests include REPM electric machines drives, power converters.