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Study of Fault-tolerant Strategy of Modular Hub Motor

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Summary

Due to the complex operating environment, higher requirements for fault tolerance are proposed to direct-drive hub motor. Multi-unit modular hub motor is a common design scheme for fault tolerance, and removing fault modules is the commonly used strategy, however, the workload of healthy modules will increase significantly, which brings in heat risk. In order to alleviate the above problems, this paper studies different fault-tolerant strategies for four-element modular hub motor under open-circuit and short-circuit faults making fully use of the healthy winding in fault unit. Firstly, the inverter topology suitable for multi-unit modular hub motor to realize fault tolerance function is discussed, and then the motor performance under circuit faults is analyzed. Through theoretical analysis and simulation verification, different fault-tolerant strategies under open circuit and short circuit faults are derived and analyzed respectively. This work provides reference to the study of fault tolerance strategy for modular hub motor.

Keywords: modular hub motor, fault-tolerant strategy, motor performance，open circuit, short circuit

1 Header

As the core technology of distributed drive of new energy vehicles, hub motor is widely favored by the new energy vehicle industry [1-3]. The hub motor is generally arranged in the hub, with compact space and severe operating environment, which puts forward strict requirements for system reliability and fault-tolerant operating under fault state.

The multi-unit modular design makes the hub motor system with redundant fault-tolerant function, which can easily realize magnetic and thermal isolation, and effectively inhibit the diffusion of failure hazards. Each unit motor can work independently or concurrently, ensuring the reliable operation of the system [4,5]. In case of winding fault, in order to ensure the output torque equivalent to the normal state, the fault module can generally be removed to make the remaining healthy modules continue to work, but the working load of the healthy module increases, which is likely to introduce hidden troubles. Therefore, in order to reduce the workload and motor loss of the remaining healthy modules, the fault module must operate under a certain fault-tolerant strategy, and the torque distribution principle of each module also needs to be adjusted.

In order to explore the above problems, this paper focuses on the fault-tolerant strategy of four-unit modular hub motor. Firstly, the inverter topology suitable for multi−unit modular hub motor to realize fault-tolerant function is discussed [6-8], then the electromagnetic and thermal characteristics of the motor under open circuit and short circuit faults are analyzed, and the fault-tolerant strategies for open circuit and short circuit faults are discussed and studied respectively. Finally, the motor performance is verified by simulated open circuit fault test.

2 Fault-tolerant inverter topology of hub motor

In order to realize the fault-tolerant function of hub motor system, it is necessary to consider not only the design of motor, but also the topology of inverters, so as to realize the effective fault-tolerant control of each motor module [9]. Some common inverter topologies are discussed as below.

2.1 Neutral point interconnection scheme

For three-phase AC motor, the inverter normally adopts three-phase half bridge topology (as shown in Figure 1). Since the sum of three-phase currents is not always zero when the motor fails, it is necessary to provide a special loop for zero sequence current. Therefore, to realize the fault-tolerant performance of hub motor under fault, the topology of inverter for motor drive is also different from that of general system.

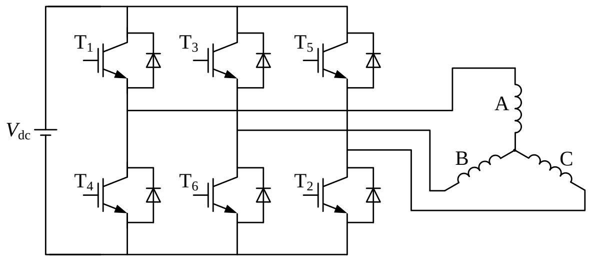


Figure 1: Three phase half-bridge topology

For multi-unit modular motors, to realize fault-tolerant operation in fault cases, the neutral points of the motor windings of each module can be interconnected through bidirectional thyristors, so that the zero sequence current of the fault module can be introduced into the three-phase winding of the health module. The additional cost of module interconnection topology is relatively low, but the control method is complex, and it is necessary to sacrifice certain performance of health modules to meet the fault-tolerant operation of fault module. In cases of faults, the health modules and fault modules cannot be effectively isolated. To realize the independent control operation of each module motor, the fault-tolerant control scheme of single motor is generally adopted.

2.2 Three phase H-bridge scheme

The three-phase H-bridge circuit can not only realize the independent control of each module of the hub motor, but also realize the independent control of the three-phase winding of each module with high reliability. Its topology is shown in Figure 2. Meanwhile, the withstand voltage of power devices is also reduced compared with the three-phase half bridge topology. However, the disadvantages of H-bridge circuit are obvious as well: compared with the three-phase half bridge structure, the number of power devices is doubled, as a result, the volume, weight and cost of inverter are significantly increased.

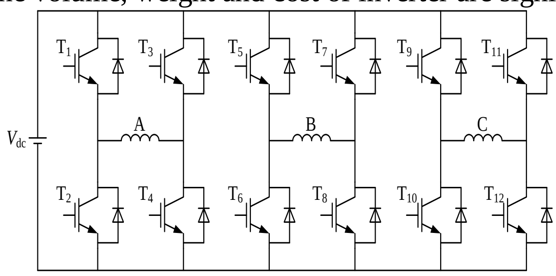


Figure 2: Three phase H-bridge topology

2.3 Two-phase four-switch scheme

The topology of the two-phase four-switch inverter is shown in Figure 3. The neutral point of the three-phase winding is connected to the capacitor midpoint of the power bus through the bidirectional thyristor. When one winding fails, the corresponding phase is cut off through the closed control signal, and the bidirectional thyristor begins to conduct, the remaining two-phase winding current is connected from the neutral point of the three-phase winding to the midpoint of the bus to form a zero sequence current circuit. The topology of two-phase four switch structure is relatively simple. Compared with the three-phase half bridge topology, only one bidirectional transistor needs to be added, and the additional cost is relatively low. However, the zero sequence current entering the middle point of the bus will lead to large ripple in the capacitive current, especially under heavy loads, the bus voltage fluctuation is more serious. Multiple inverters share the same bus in a modular motor system, so this fault-tolerant structure is not suitable.

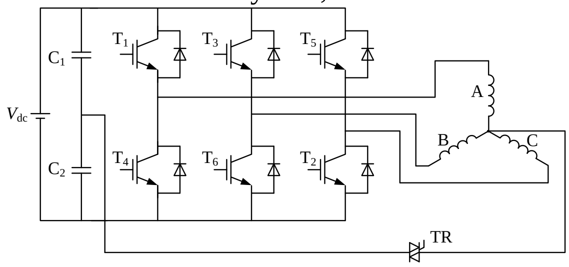


Figure 3: Two-phase four switch structure topology

2.4 Three-phase four-leg scheme

For multi-modular hub motor with one power bus, the fault-tolerant topology commonly used in engineering is the three-phase four-leg topology, as shown in Figure 4. When the system works normally, the bidirectional thyristor is disconnected, the fourth bridge leg is not put into operation, and the inverter works as a three-phase half bridge inverter. When the winding fails, the fault winding is cut off and the two-phase thyristor triggers to conduct at the same time to put the fourth bridge leg into operation to provide a loop for zero sequence current. Compared with the two-phase four-switch topology, although the three-phase four-leg topology equips with one bridge arm additionally, but alleviate requirements for the bus capacitance and is of high reliability.

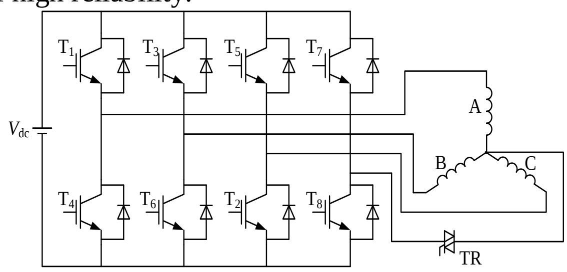


Figure 4: Three-phase four-leg topology

2.5 Topology scheme selection of fault tolerant inverter

The modular hub motor is improved from the traditional hub motor, which is divided into several modules in the circumferential direction of the motor stator. Each stator module equips with an independent three-phase AC winding and is powered by an independent inverter. For the four-unit modular hub motor, the comparison results of the above four different inverter topologies are shown in Table 1.

Table1 Comparison of four module In-wheel motor with different Inverters topology

Project	Neutral point interconnection scheme	Three phase H-bridge topology	Two-phase four-switch structure topology	Three-phase four-leg topology
Number of IGBTs	24	48	24	32
Number of bidirectional thyristors	4	0	4	4
Advantage	Low additional cost	High reliability	Low additional cost	High reliability

Disadvantage	The control is complex, and the module cannot operate independently in case of failure	High additional cost, the increase of volume and weight of the inverter are significantly	Bus voltage fluctuation is serious	Add one bridge arm for each module

Considering the system reliability and the additional cost of the inverter, the three-phase four-leg topology of the inverter is more suitable. All modules share one rotor and all inverters share the same bus voltage. The fault-tolerant system of modular hub motor is shown in Figure 5.

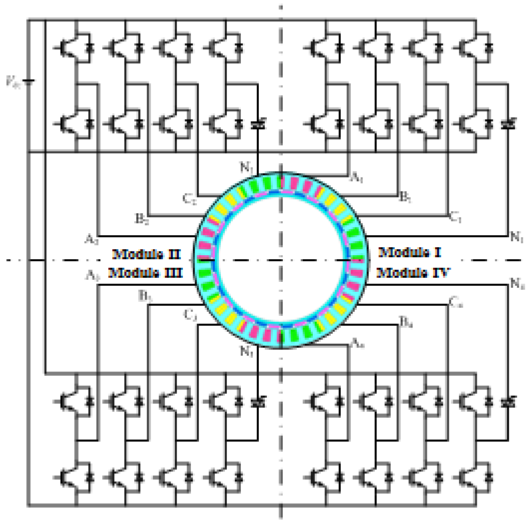


Figure 5: Modular hub motor topology

During normal operation, the stator windings of each module of hub motor are connected with three-phase symmetrical current to jointly drive the rotor to rotate according to the principle of average torque distribution [10]. At this time, each module generates a traveling wave magnetic field in the air gap and a rotating magnetic field together in the air gap of the motor, which is the same as the traditional permanent magnet hub motor. In case of winding fault (such as open circuit on a phase winding of one module), the fault module can be removed and the remaining healthy module can continue to work. To maintain the same output as a whole, the winding current and output torque of the healthy module are obviously greater than those under normal operation. In order to alleviate the workload and motor loss of the remaining healthy modules, the fault module is supposed to operate under a certain fault-tolerant strategy. At this time, the torque distribution principle of each module also needs to be adjusted. In the following part, the motor characteristics under fault state are analyzed, and then the fault-tolerant strategies of modular hub motor under open circuit and short circuit faults are discussed.

3 Motor performance analysis under fault state

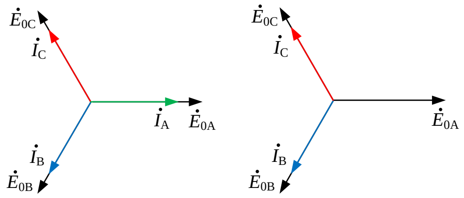
3.1 Electromagnetic analysis of motor under open circuit fault

Open circuit fault is the most common fault in motor operation. During normal operation, the stator windings of each motor unit are conducting with three-phase symmetrical current which is in the same phase with the corresponding no-load back EMF, named "$i_d = 0$" control strategy. At this time, the electromagnetic torque of the unit motor can be expressed as:

$$T_e = \frac{e_{0A} i_A + e_{0B} i_B + e_{0C} i_C}{\Omega} = \frac{3E_0 I}{\Omega} \qquad (1)$$

E_{0A} and i_A in the formula represent the back electromotive force and current of a phase respectively, Ω represents the rotor speed.

When open circuit fault occurs in one phase winding (assuming A phase winding), the current of the fault phase winding disappears. The three-phase current phasor of the fault module before and after the open circuit fault is shown in Figure 6.



a) Before fault b) Aafter fault

Figure 6: Three phase current phasor before and after open circuit fault

After the open circuit fault, the electromagnetic torque of the unit motor becomes:

$$T_e = \frac{e_{0B} i_B + e_{0C} i_C}{\Omega} \quad (2)$$

It can be seen from formula (2), The electromagnetic torque of the fault module motor is reduced to 2/3 compare with the normal state, and for the four-unit hub motor, the electromagnetic torque is reduced to 11/12 of the normal working. After the three-phase winding of the fault module is cut off, only three unit motors are left to work, so the electromagnetic torque decreases to 3/4 of the normal state.

3.2 Thermal analysis of motor under open circuit fault

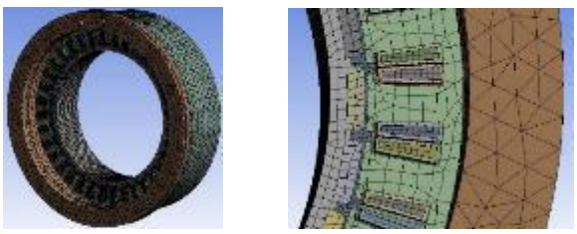
Considering hub motor is of good sealing performance and the heat dissipation effect of water-cooled motor is generally much better than other heat dissipation methods, it can be supposed that the heat generated by motor loss is mostly taken away by the coolant in the pipeline. Therefore, the following factors are ignored in the heat transfer of modular hub motor:

(1) Heat conduction between the inner surface of the rotor and the bearing;

(2) Natural convection between motor end and air;

(3) Heat radiation at the end of the motor and the outer surface of the casing.

After a series of assumptions, equivalences and simplifications, the temperature field model of multi-unit modular hub motor is finally transformed into an unsteady heat conduction problem with boundary conditions. The network division of the calculation model is shown in Figure 7.



a) Whole model B) Local magnification

Figure 7: Mesh subdivision of the thermal field model

Assuming that the initial temperature of the motor is 70 ℃, when an open circuit fault occurs in one phase winding of a module of the hub motor, the steady-state temperature field obtained by finite element simulation is shown in Figure 8. At this time, there is no current in the phase winding under open circuit fault, no copper consumption as well. Therefore, the temperature is significantly lower than that of other windings, and the temperature of stator teeth wound by the fault phase winding is also relatively low.

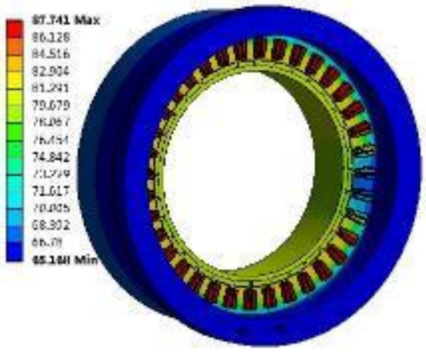


Figure 8: Thermal distribution of hub motor under open circuit fault

It is noted that since the thermal field model of the hub motor regards the rotor as stationary, the influence of rotor rotation on the thermal distribution is not taken into account. Although Figure 8 shows that the temperature of the rotor permanent magnet and rotor core close to the fault phase winding is relatively low, in fact, due to the rotation of the rotor, any permanent magnet on the rotor may be rotated close to the fault phase winding. Therefore, even if the modular hub motor operates asymmetrically, the thermal distribution of each permanent magnet in the rotor is roughly the same, and the temperature of the rotor core is evenly distributed in the circumferential direction.

3.3 Vibration Analysis of motor under open circuit fault

When an open circuit fault occurs in one phase winding (assuming A phase winding) of modular hub motor, the electromagnetic force on the center point of stator teeth is simulated and showed in Figure 9. Compared with normal operation, the amplitude of radial air-gap electromagnetic force at the stator teeth wound by open circuit winding will decrease, the tangential component of air-gap electromagnetic force at the corresponding notch will increase, and the peak value is higher than that of other healthy modules.

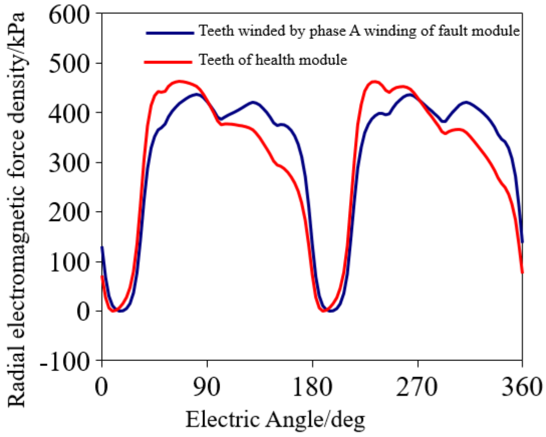


Figure 9: Oscillogram of stator tooth force under open circuit fault

3.4 Electromagnetic analysis of motor under short circuit fault

When a short-circuit fault occurs at the end of a phase winding (assumed to be phase a winding), back EMF in phase is generated while the rotor rotating and short-circuit current i_{sc} is generated in the winding, as shown in Figure 10. When the short-circuit current is steady, it is a sinusoidal current, that is

$$i_{\mathrm{sc}} = \sqrt{2}I_{\mathrm{sc}}\,cos(\omega t + \varphi_{\mathrm{sc}}) \qquad (3)$$

Since the armature winding is resistive and inductive, and its resistance is small, so φ_{sc} is slightly greater than 90°. Similar with the open circuit fault, the short circuit fault will also cause the decrease of electromagnetic torque and a secondary fluctuation of torque in a cycle. However, compared with the open circuit fault, the electromagnetic torque caused by the short circuit fault decreases and fluctuates more violently, and the heat problem of the motor caused by the increase of copper consumption of the fault winding is more serious.

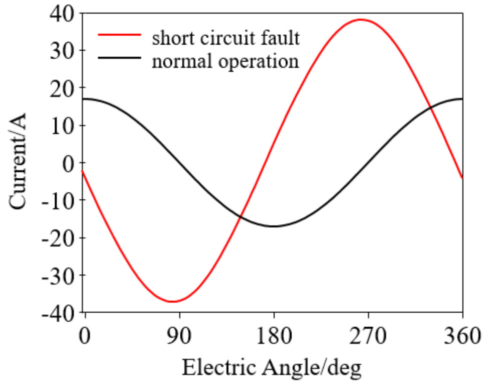


Figure 10: Short circuit current waveform

3.5 Thermal analysis of motor under short circuit fault

Assuming that the initial temperature of the motor is 70 ℃, when the short circuit fault occurs in one phase winding end of one unit motor, the thermal field of the motor under the action of water cooling obtained by finite element simulation is shown in Figure 11. At this time, the short-circuit fault winding will have a large current, and its copper consumption and temperature rise are much higher than other windings. The thermal distribution on the stator core is uneven, and the temperature of the stator teeth wound by the short-circuit phase winding is high. The temperature rise of rotor permanent magnet and yoke is slow. When the motor operates for 180s, the rotor temperature is less than 90 ℃, while the short-circuit fault winding temperature reaches 142 ℃. Since the heat generated by the short-circuit current cannot be taken away by the coolant in time, the motor is not suitable for long-term continuous operation under short-circuit fault.

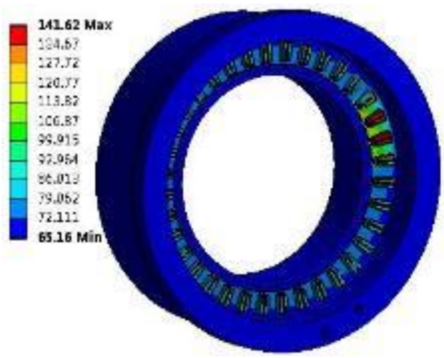


Figure 11: Thermal distribution of hub motor under short circuit fault (operating for 180s)

It can be seen from the above analysis that the motor torque will drop sharply and thermal distribution change dramatically regardless of open-circuit fault or short-circuit fault, which brings in great harm in vehicle operation. Therefore, it is necessary to study the corresponding fault-tolerant strategies for open circuit and short circuit faults.

4 Research on fault-tolerance strategy of open circuit

Under open circuit fault of the hub motor, all windings of the fault module can be cut off. The previous analysis shows that the torque of the motor decreases to 3/4 compare with normal state. In order to ensure the output torque of the hub motor remains unchanged, the output torque of the remaining three health modules has to increase to 4/3 as before. According to formula (1), the three-phase current of the health module needs to be increased to 4/3 as before. The calculation formula of Joule copper loss of unit motor is normally as follows:

$$\mathrm{P_{cu}} = I_A^2 R_s + I_B^2 R_s + I_C^2 R_s \qquad (4)$$

Where I_A 、 I_B 、 I_C represents the phase current of three windings respectively, R_S represents the phase resistance of the motor winding. At this time, there is no current in the three-phase winding of the fault module, and no copper consumption. The copper consumption of the other three healthy unit motors is 16/9 times of their normal operation. Obviously, compared with the normal state, the overall copper consumption is 4/3 times of the normal operation.

In order to reduce the working load and copper consumption of the remaining healthy module, it is necessary to make effective use of the remaining two-phase windings of the faulty module. At present, the commonly adopted method is the fault-tolerant strategy of magnetomotive force compensation. It is easy to conclude from the AC winding theory of electrical machine that the three-phase synthetic magnetomotive force can be expressed as:

$$f = f_A + f_B + f_{AC} = \frac{3\sqrt{2}}{\pi}\frac{Nk_{w1}}{p} I\cos(\omega t - \theta_s) \qquad (5)$$

Where N is the number of series turns per phase, k_{w1} is the winding factor of fundamental wave, I is the number of poles of the motor, and I is the effective value of phase current, w is the angular speed of motor rotation, θ_s is the electrical angle of the motor.

When A phase winding of one module is under open circuit fault, the magnetomotive force generated by phase B and C can be expressed as:

$$f^{\cdot} = f_B + f_C = \frac{4}{\pi}\frac{Nk_{w1}}{2p}[i_B \cos\left(\theta_s - \frac{2\pi}{3}\right) + i_C \cos(\theta_s + \frac{2\pi}{3})] \qquad (6)$$

In order to compensate for the loss of magnetomotive force caused by the failure of A phase, it is necessary to readjust the amplitude and phase of the winding current of phase B and C, to make the magnetomotive force generated by the winding of the fault module consistent as normal state, then the current of phase B and C can be obtained, as shown in formula (7):

$$\begin{cases} i_B = \sqrt{6} I \cos\left(\omega t - \frac{5\pi}{6}\right) \\ i_C = \sqrt{6} I \cos\left(\omega t + \frac{5\pi}{6}\right) \end{cases} \qquad (7)$$

The fault module adopts the magnetomotive force compensation strategy, meanwhile, adjusts the torque distribution of each module to realize the fault-tolerant operation of modular hub motor under open circuit fault. The open circuit fault tolerance performance of modular hub motor under three different current distribution principles of magnetomotive force compensation strategy is discussed below, as principle of equal torque, principle of equal current and principle of minimum copper consumption.

4.1 Principle of equal torque

Under this principle, the torque distribution ratio of each module is adjusted to 1:1:1:1. For the fault module, assuming that A phase winding occurs open circuit fault, according to formula (7), the current of the remaining two-phase winding needs to be $\sqrt{3}$ times of that under normal operation, the current phase of phase B winding is adjusted to be 30 °behind its no-load back EMF, and the current phase of phase C winding is adjusted to be 30 °ahead of its no-load back EMF. The three-phase currents and phases of the left healthy modules remain unchanged.

According to the copper loss formula (4), the copper loss of the remaining two-phase winding of the fault module increases by twice as much as that before the fault. The overall copper consumption of hub motor is 1.25 times compared with normal state.

4.2 Principle of equal current

It is assumed that except for the open circuit fault winding, the current of all windings is k times that of normal operation. At this time, except for the open circuit fault winding, the copper consumption and heat source of other windings are evenly distributed, which is conducive to the heat dissipation of the motor. Ignoring the influence of motor core saturation, it is considered that the electromagnetic torque is of a linear relationship with armature current. To maintain the same electromagnetic torque as before, while all the winding currents equal, the equation can be derived as follows:

$$\frac{T_e}{M}\left[(M-1)k + \frac{k}{\sqrt{3}}\right] = T_e \qquad (8)$$

So:

$$k(M) = \frac{\sqrt{3}M}{\sqrt{3}M - \sqrt{3} + 1} \qquad (9)$$

Where M is the number of sub module motors. In this paper, $M = 4$, so $k = 1.118$ is obtained. At this time, the torque distribution ratio of each module is adjusted to 0.577:1:1:1, in which the output torque of the fault module is the smallest. For the fault module, it is assumed that the A phase winding occurs open circuit fault , the current of the remaining two-phase winding is 1.118 times that of the normal operation, the current phase of phase B winding is adjusted to be 30 °behind its no-load back EMF, and the current phase of phase C winding is adjusted to be 30 °ahead of its no-load back EMF. The three-phase current of the remaining health module is 1.118 times that of normal operation, the phase remains unchanged, and the copper consumption is 1.25 times that of normal operation. The copper consumption of fault module is reduced to 83.4% of that of normal operation, and that of health modules is increased to 1.25 times of that of normal operation. The copper consumption of hub motor is 1.146 times compared with normal state.

4.3 Principle of minimum copper consumption

Assuming that the winding current of M modules increases to k_1, k_2 ..., k_M of the normal working current, where k_1 is the current amplitude increase multiple of the remaining two-phase winding of the fault module. To ensure that the output electromagnetic torque is consistent with that before open circuit fault, the following equation can be listed:

$$\frac{T_e}{M}\left[\frac{k_1}{\sqrt{3}} + k_2 + k_3 + \cdots + k_M\right] = T_e \tag{10}$$

At this time, the copper consumption of the motor is:

$$\begin{aligned} P_{cu} &= 2(k_1 I)^2 R + 3(k_2 I)^2 R + \cdots + 3(k_{M-1} I)^2 R + 3(k_M I)^2 R \\ &= I^2 R\left(2{k_1}^2 + 3{k_2}^2 + \cdots + 3{k_{M-1}}^2 + 3{k_M}^2\right) \end{aligned} \tag{11}$$

The minimum value of copper loss is obtained by Lagrange multiplier method:

$$\begin{cases} k_1 = \frac{\sqrt{3}M}{2M-1} \\ k_2 = \cdots = k_M = \frac{2M}{2M-1} \end{cases} \tag{12}$$

In this paper, $M = 4$, so:

$$\begin{cases} k_1 = 0.99 \\ k_2 = k_3 = k_4 = 1.143 \end{cases}$$

For the fault module, it is assumed that the A phase winding occurs open circuit fault, the current of the remaining two-phase winding is 0.99 times that of the normal operation, the current phase of B winding is adjusted to be 30 °behind its no-load back EMF, and the current phase of C winding is adjusted to be 30 ° ahead of its no-load back EMF. The three-phase current of the remaining health module is 1.143 times that of normal operation, and the phase remains unchanged. The torque distribution ratio of each module is adjusted to 0.5:1:1:1, in which the output torque of the fault module is the smallest.

The current of health module is 1.143 times of normal operation, and the copper consumption is 1.306 times of normal operation. The remaining two phase currents of the open circuit fault module is 0.99 times of the normal state, the copper consumption is 0.98 times of the normal working, and the copper consumption of the fault module is reduced to 65.3% of the normal state. The copper consumption of hub motor is 1.143 times compared with normal state.

4.4 Comparison of electromagnetic torque under different open circuit fault tolerance strategies

The electromagnetic torques of the 4-module hub motor under normal operation, open-circuit fault of one-phase winding and open-circuit fault tolerance strategy are simulated and are shown in Figure 12.

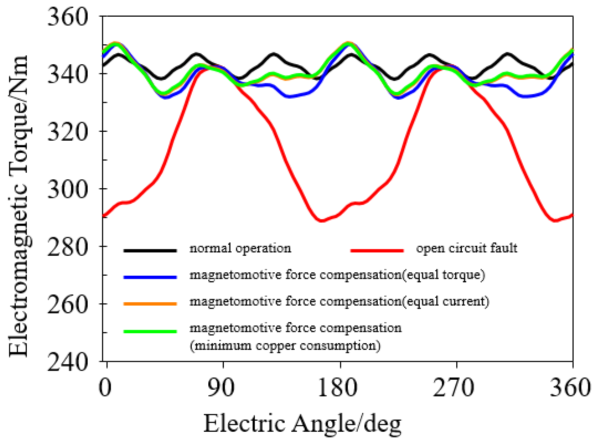


Fig.12 Electromagnetic torque of hub motor under normal operation, open circuit fault and fault tolerance

Due to the existence of the third harmonic in the back EMF, the electromagnetic torque fluctuates four times in one cycle. After adopting the fault-tolerant strategy of magnetomotive force compensation, the electromagnetic torque is slightly lower than that in normal operation, and the difference between them is less than 1%, which is caused by the stator core saturation under increase of armature current. Compared with the equal torque principle, the fault-tolerant strategy of magnetomotive force compensation under the principle of equal current and minimum copper consumption can make the electromagnetic torque of the motor closer to normal operation, and remaining minimum motor copper consumption.

5 Research on fault-tolerance strategy of short circuit

In case of short-circuit fault of modular hub motor, the short-circuit current always exists, even when the fault module is removed, and the electromagnetic torque will fluctuate twice in one cycle. Therefore, the short-circuit fault module has to continue operating under certain fault-tolerant strategies. At present, the methods adopted for motor short-circuit fault contain magnetomotive force compensation fault-tolerant strategy and electromagnetic power compensation fault-tolerant strategy. For electromagnetic power compensation fault-tolerance strategy, there are two principles under different torque distribution: equal torque distribution principle and minimum copper consumption principle.

5.1 Fault tolerant strategy of magnetomotive force compensation

In case of short circuit fault of A phase winding, the magnetomotive force generated by the motor can be expressed as:

$$f^{\cdot\cdot} = f_B + f_C = \text{phase}\frac{4}{\pi}\frac{Nk_{w1}}{2p}\left[i_{SC}\cos\theta_s + i_B\cos\left(\theta_s - \frac{2\pi}{3}\right) + i_C\cos(\theta_s + \frac{2\pi}{3})\right] \quad (13)$$

The magnetomotive force generated by the winding of the fault module before and after fault can be consistent by changing the current magnitude of B and C phase windings. The current of phase B and C windings after short- circuit fault can be expressed as:

$$\begin{cases} i_B = i_{SC} + \sqrt{6}I\cos\left(\omega t - \frac{5\pi}{6}\right) \\ i_C = i_{SC} + \sqrt{6}I\cos\left(\omega t + \frac{5\pi}{6}\right) \end{cases} \quad (14)$$

According to formula (14), during fault-tolerant operation, the remaining two-phase windings of the short-circuit fault module need to add the short-circuit current with the same amplitude and phase as the short-circuit winding i_{sc} to eliminate the magnetomotive force generated by A phase short-circuit current, and add the same current as the open circuit fault tolerance to generate electromagnetic torque.

5.2 Fault tolerant strategy of electromagnetic power compensation on equal torque distribution principle

When A phase winding occurs short circuit fault, according to the principle of constant electromagnetic power, the current of phase B and C can be conducted by taking the minimum copper consumption of short-circuit fault module as the optimization objective. The phase difference φ_{sc} between short-circuit current and no-load back EMF is approximately 90 °, and the expression of fault-tolerant current of phase

B and phase C can be derived as:

$$\begin{cases} i_B = \sqrt{2}\left(\frac{I_{sc}}{2} - \sqrt{3}I\right)\cos\left(\omega t + \frac{\pi}{6}\right) \\ i_C = \sqrt{2}\left(\frac{I_{sc}}{2} + \sqrt{3}I\right)\cos\left(\omega t + \frac{5\pi}{6}\right) \end{cases} \quad (15)$$

Fault-tolerant operation of modular hub motor under short-circuit fault can be realized adopting the short-circuit fault-tolerant strategy based on electromagnetic power compensation, meanwhile, adjusting the torque distribution of each module. Equal torque principle can be applied under this condition, which means torque distribution ratio of each module is 1:1:1:1. The three-phase current of the health module remains unchanged before and after the fault, as a result, current and copper consumption of two phase winding of the fault module increase a lot. However, compared with the magnetomotive force compensation strategy above, the currents of the remaining two phases reduce slightly.

5.3 Fault tolerant strategy of electromagnetic power compensation on minimum copper consumption principle

Increasing the output electromagnetic torque of the health module can reduce the working load of the short-circuit fault module in certain extent. To maintain constant electromagnetic torque, it is assumed that the current of remaining two phase winding in the fault unit is k_1 times that under normal state , as follows:

$$\begin{cases} i_B = \frac{\sqrt{2}}{2}I_{sc}\cos\left(\omega t + \frac{\pi}{6}\right) + \sqrt{2}k_1 I\cos(\omega t - \frac{5\pi}{6}) \\ i_C = \frac{\sqrt{2}}{2}I_{sc}\cos\left(\omega t + \frac{5\pi}{6}\right) + \sqrt{2}k_1 I\cos(\omega t + \frac{5\pi}{6}) \end{cases} \quad (16)$$

The winding current of the other three health modules increases to k_2 times of normal operation. supposing the hub motor reaches the same electromagnetic torque with normal state and taking the minimum copper consumption as the optimization goal, k_1 and k_2 can be solved.

The current of health module is 1.143 times that of normal operation, and the copper consumption is 1.306 times that of normal operation for the four-unit modular hub motor. The currents of two phases in the short-circuit fault module is greater than that in the health modules, while the current in the left phase is relatively small. The copper consumption of fault module is relatively large, however, it gets reduction compared with equal torque principle.

5.4 Comparison of electromagnetic torque of hub motor under different short-circuit fault-tolerant strategies

The electromagnetic torques of the four-unit modular hub motor under normal operation, short-circuit fault and different short-circuit fault tolerance strategies are verified by simulation, as shown in Figure 13. After the short-circuit fault occurs, the electromagnetic torque decreases sharply, and two large torque fluctuations appears in one cycle. The fault-tolerant strategy of magnetomotive force compensation can improve the electromagnetic torque and reduce the torque fluctuation, but the fault-tolerant current of the remaining two phase windings of the short-circuit fault module becomes large. The fault-tolerant strategy of electromagnetic power compensation can make the electromagnetic torque close to the normal state, and the torque fluctuation and copper consumption are smaller. Compared with equal torque distribution, the electromagnetic torque is closer to normal state, when the torque distribution of each module meets the minimum copper consumption principle.

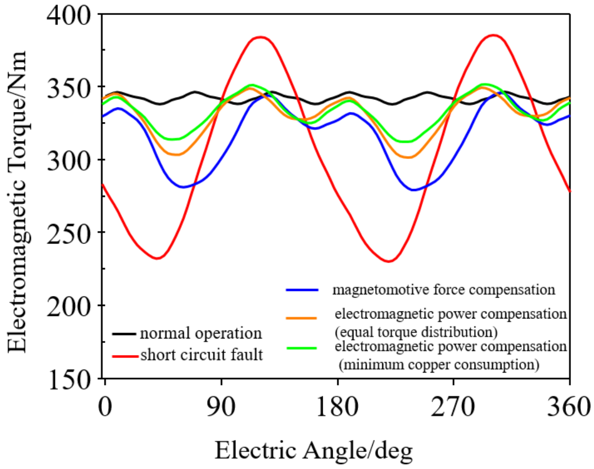


Fig.13 Electromagnetic torque of hub motor under normal operation, short circuit fault and fault tolerance

6 Experiment analysis

In order to verify some simulation calculation results, the experiment platform is constructed as shown in Figure 14. The experiment simulates the open circuit fault of the modular hub motor, adopting the strategy of cutting off the whole fault unit motor, and phase currents of other healthy unit motors were collected. On condition that the output torque of the hub motor remains unchanged, the phase currents of the hub motor unit motor before and after fault occurs are compared. As shown in Figure 15, the amplitude of phase current increases to 4/3 times of that before the fault, which is consistent with the theoretical analysis.

Figure 14: Test of prototype

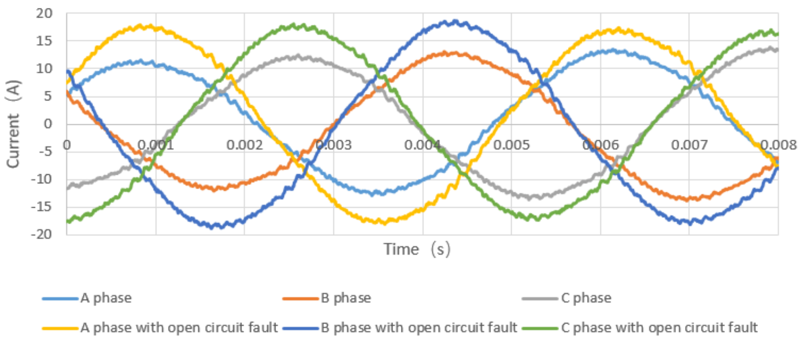


Figure 15: Unit motor line current of In-Wheel motor under normal operation and open circuit fault

In addition, since it is difficult to collect the vibration data of one single tooth in the test, the vibration sensor is placed on the corresponding shell of each unit motor to collect vibration data in the test. The vibration data of the hub motor under normal operation and open circuit fault is explored and studied, as shown in the radar map of Figure 16. Through the motor shell vibration test, it can be seen that the vibration amplitude of the motor increases from 2.8mm to 4.9mm, approximately 77%, after the open circuit fault. The intensification of motor vibration is mainly from the unbalanced magnetic pull while one direction electromagnetic force weakened after open circuit fault [11,12].

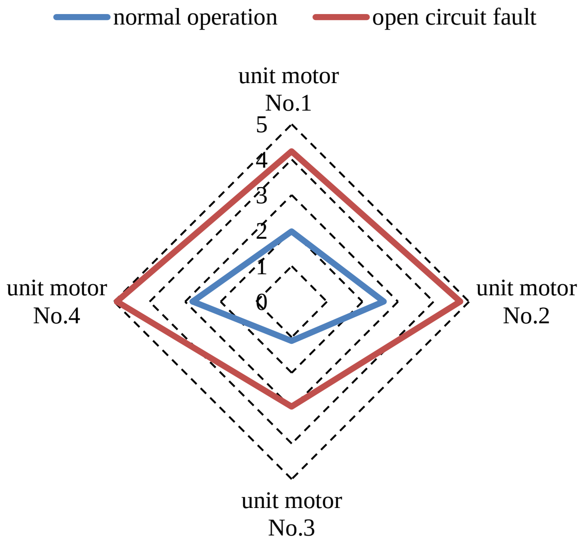


Fig.16 Vibration amplitude radar map of hub motor under normal operation and open circuit fault

7 Conclusion

Based on the topology of three-phase four-leg inverter, the fault-tolerant strategies of four-unit module hub motor are studied in this paper. Firstly, the electromagnetic and thermal characteristics of the motor under open circuit and short circuit faults are analyzed, which shows that the modular hub motor is not suitable for long-term operation under short circuit faults. The open circuit fault of one phase will lead to sharp torque decrease and large torque fluctuation. This paper discusses the compensation strategy of magnetomotive force based on the principle of equal torque, equal current and minimum copper loss. Compared with the principle of equal torque, the magnetomotive force compensation strategy based on the principle of equal current and the principle of minimum copper consumption can make the motor torque closer to the normal level and minimize the copper consumption of the motor, which is of certain application value. Short-circuit fault will also sharply decrease motor torque, introduce large torque fluctuation and aggravate the motor temperature rise. This paper discusses the magnetomotive force compensation strategy of modular motor and the electromagnetic power compensation strategy based on the principle of equal torque and minimum copper consumption. Compared with the magnetomotive force compensation strategy, the electromagnetic power compensation strategy can make the motor torque close to the normal state, and the torque fluctuation and copper consumption are the smallest, which is of more practical application value. Finally, through the multi-unit modular motor open circuit fault experiment, some motor characteristics under fault mode are verified.

This paper provides theoretical basis and analysis method for the research of fault-tolerant performance of multi-unit modular hub motor, and provides references for the research of fault-tolerant strategy of this type motor.

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