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Fault-Tolerant Control of Modular Permanent Magnet Synchronous Motor Under Open-Circuit Faults

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ABSTRACT The paper studies a novel fault-tolerant strategy of the modular permanent magnet synchronous motor under open-circuit faults, which is called as the extended open-circuit fault-tolerant control (EOCFTC) strategy. The faulty modular motor based on the EOCFTC strategy can achieve the high fault-tolerance and maximum output torque capability by making the most of the remaining healthy phases. First, the mathematical model of the modular motor with n modules is described. Then based on the characteristics of the modular motor, a novel winding reconstruction strategy is proposed to deal with multiphase open-circuit faults in different modules. All remaining healthy phases are reasonably reconstructed according to the maximum output torque principle. Then these new modules can operate well by employing the armature magnetomotive force (MMF) compensation and the field-orientated control (FOC) strategy. Finally, all cases of open-circuit faults and the corresponding processing methods are discussed. The extreme case of open-circuit faults is described in detail, which shows the high fault-tolerance of the modular motor with the EOCFTC strategy. The experimental results verify the rationality and feasibility of the EOCFTC strategy on a two-module modular motor.

INDEX TERMS Armature magnetomotive force compensation, modular permanent magnet synchronous motor, open circuit fault tolerance, winding reconstruction.

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) is one of the main energy conversion components, which has many excellent advantages such as high efficiency and high torque density [1]. The drive system of PMSM is requested to have fault tolerance capability in many industry areas [2]–[4]. For example, applied to electric vehicles, the drive system of PMSM is required to have great reliability ensuring that fault-tolerant control strategies enable the vehicle to be rated or derated operating steadily for a long period when faults occur. This ability provides sufficient time for the vehicle to continue traveling [5]. Therefore, the study of fault-tolerant motor technique is necessary.

In order to achieve the fault tolerance, the most commonly used motor structure includes multiphase and modular structure [6]. Although the multiphase motor can realize the fault-tolerant operation, the control system and strategies are complicated. Besides, we need to change all the other healthy phase windings' armature magnetomotive force (MMF) in the case of single-phase fault, causing significant torque ripple [7]–[11]. The modular motor is designed to have a number of three-phase modules, each controlled by an independent three-phase inverter [12]. When a module fails, it will be cut off from the system without affecting the health modules operating normally. This structure can not only control each module independently, but also make use of the mature three-phase motor drive techniques. Therefore, the modular topology must become the research focus for high reliability fault-tolerant motors [13]–[16].

In [13]–[15], the modular motor consists of two sets of three-phase Y-connected windings in each module. When a phase winding is open circuit, it will be cut off from the system. The other set of windings operates normally just like traditional three-phase windings. The modular motor proposed in [16] consists of eight three-phase modular units. The magnetic coupling between different modules is very little. When the motor is in fault condition, the faulty module

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can be undoubtedly cut off from the system. Although cutting off the faulty module can be simply realized and the system can achieve fault-tolerant operation, it significantly reduces the system's output capability. If there are two modules, for example, the output capability will be reduced by 1/2 p.u.; if there are n modules, the output capability will be reduced by 1/n p.u..

In order to improve the output capability of the system under fault conditions, it is necessary to conduct fault-tolerant control strategy in the faulty module so that it is capable of outputting electromagnetic torque. Reference [17] studied the optimal loss and optimal torque control strategy for a dual three-phase motor when one phase is open. Aiming at the single-phase open-circuit fault of different modules, the method of neutral point interconnection is proposed in [18], [19]. The above fault-tolerant methods are complicated and need to sacrifice electromagnetic performance of the normal modules, resulting in a decrease of the overall system performance. Due to the independence of the three-phase modules in the modular motor, it is more suitable to conduct existing fault-tolerant control strategy of three-phase motor in the faulty modules [6]. The basic theory of the traditional fault-tolerant strategies for three-phase PMSM is to compensate the MMF after single-phase open-circuit fault occurs [20]. The neutral point needs to be used in this case. There are two different ways to realize this theory, which are employing the topologies with split capacitor [21] and with redundant leg [22], [23]. In the first topology, the neutral point is linked to the midpoint in DC bus by splitting the capacitor, which can cause large voltage fluctuations of bus voltage and is not suitable for the modular motor [21]. The second topology is to add a redundant leg for the neutral point, which is easy to be imported to the modular motor [22], [23].

So far, the open-circuit fault investigated above is the single-phase fault. The existing fault-tolerant strategies of three-phase PMSM have no means of dealing with two-phase open-circuit fault for the three-phase module of the modular motor. It is a waste that the remaining single healthy phase of the fault module to be cut off. So, it is worth to develop a fault-tolerant strategy for the modular motor which can utilize all possible healthy phases to achieve the maximum output torque capability under multiphase open-circuit fault.

This paper proposes a novel open-circuit fault-tolerant control strategy for a modular permanent magnet synchronous motor with n modules, which is called as the extended open-circuit fault-tolerant control (EOCFTC) strategy. The topology with redundant leg is chosen as the fault-tolerant topology of each three-phase module. Due to the convenience and reliability of using well-developed algorithms of three-phases drives for each module, the field-orientated control (FOC) and MMF compensation strategy are employed for the normal and single-phase open-circuit fault-tolerant operation respectively. In order to achieve the optimal fault-tolerance under multiphase open-circuit faults of the modular motor, a winding reconstruction strategy is then studied based on the characteristics of the modular motor. The usages of the remaining healthy phases are not limited within their own modules. The faulty phases can be replaced by the healthy ones from other modules. So, the remaining single healthy phases in the modules under two-phase open-circuit fault can be reused. Then the reconstructed modules can be controlled by the two strategies mentioned above. By employing the EOCFTC strategy, the maximum output torque capability of the modular motor can be achieved. All multiphase open-circuit faults are discussed, and the extreme case in which there are only two healthy phases left is mentioned specially, which shows the high fault-tolerance of the modular motor with the EOCFTC strategy. Experiments are performed on the minimum modular motor (two modules), which prove that the proposed fault-tolerant control system is reasonable and feasible.

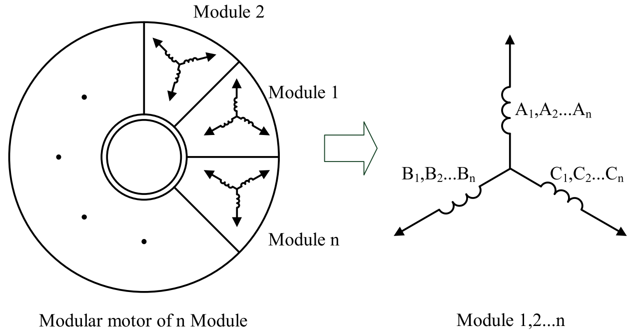

FIGURE 1. Equivalent chart of the modular motor with n modules.

The remainder of this paper is organized as follows. The mathematical model of the modular motor with n modules is described in Section II. The single-phase open-circuit fault-tolerant strategy for modular motor are investigated in Section III. Then the proposed multiphase open-circuit fault-tolerant strategy for modular motor are developed in Section IV. The experimental results are shown in Section V. A brief conclusion is presented in Section VI.

II. MATHEMATICAL MODEL OF MODULAR MOTOR

The stator of the modular motor is divided into modules along the circumference. Each stator module is a set of independently controlled three-phase windings. Assuming that the number of modules is n, the stator windings of each module in the modular motor system are all three-phase Y-connected symmetrical windings. Each module has the same electrical position and the corresponding phase has the same electrical angle. Fig. 1 illustrates this characteristic of the modular motor. So, each module's three-phase current equation is of the same form, as

$$\begin{cases} i_{\mathrm{A1,2...n}} = I_{\mathrm{m1,2...n}} \cos(\omega_{\mathrm{e}} t) \\ i_{\mathrm{B1,2...n}} = I_{\mathrm{m1,2...n}} \cos\left(\omega_{\mathrm{e}} t - \dfrac{2}{3}\pi\right) \\ i_{\mathrm{C1,2...n}} = I_{\mathrm{m1,2...n}} \cos\left(\omega_{\mathrm{e}} t + \dfrac{2}{3}\pi\right) \end{cases} \quad (1)$$

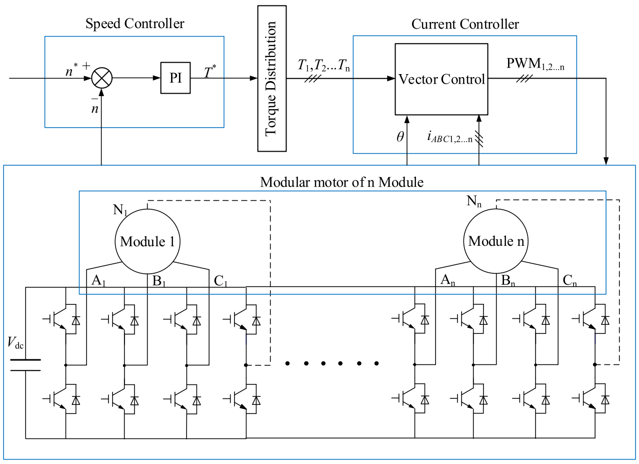

FIGURE 2. Modular motor control system diagram.

where $I_{m1,2\ldots n}$ is the amplitude of phase current of each module; ω_e is the electrical angular frequency.

In the d-q coordinate system, the voltage equation of the modular motor is

$$\begin{bmatrix} U_{dq1} \\ \vdots \\ U_{dqn} \end{bmatrix} = \begin{bmatrix} A_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & A_n \end{bmatrix} \begin{bmatrix} I_{dq1} \\ \vdots \\ I_{dqn} \end{bmatrix} + \begin{bmatrix} B_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & B_n \end{bmatrix} \times \frac{d}{dt} \begin{bmatrix} I_{dq1} \\ \vdots \\ I_{dqn} \end{bmatrix} + \begin{bmatrix} C_1 \\ \vdots \\ C_n \end{bmatrix} \quad (2)$$

where $U_{dq1,2\ldots n} = \left[U_{d1,2\ldots n} \; U_{q1,2\ldots n} \right]^T$, $U_{q1,2\ldots n}$, $U_{d1,2\ldots n}$ are the q- and d-axis voltages of each module, respectively; $I_{dq1,2\ldots n} = \left[I_{d1,2\ldots n} \; I_{q1,2\ldots n} \right]^T$, $I_{q1,2\ldots n}$, $I_{d1,2\ldots n}$ are the q- and d-axis currents of the each module, respectively; $\mathbf{A}_{1,2\ldots n} = \begin{bmatrix} R_{s1,2\ldots n} & -L_{q1,2\ldots n}\omega_e \\ L_{d1,2\ldots n}\omega_e & R_{s1,2\ldots n} \end{bmatrix}$, $\mathbf{B}_{1,2\ldots n} = \begin{bmatrix} L_{d1,2\ldots n} & 0 \\ 0 & L_{q1,2\ldots n} \end{bmatrix}$, $\mathbf{C}_{1,2\ldots n} = \begin{bmatrix} 0 \\ \omega_e \psi_f \end{bmatrix}$, $R_{s1,2\ldots n}$, $L_{d1,2\ldots n}$ and $L_{q1,2\ldots n}$ are the phase winding resistance, q- and d-axis inductance of each module; ψ_f is the PM flux linkage.

The total output torque of the modular motor with n modules is

$$T_e = \sum_{i=1}^{n} T_{ei} = \frac{3}{2} p \left\{ \psi_f \sum_{i=1}^{n} I_{qi} + \sum_{i=1}^{n} [(L_{di} - L_{qi}) I_{di} I_{qi}] \right\} \quad (3)$$

where T_e is the output torque of the modular module;p represents the number of pole pairs.

It can be clearly seen from the above analysis that by employing the FOC strategy for each module, we can control the modular motor operating under normal case. The topology of the modular motor control system is shown in Fig. 2. In this way, through reasonable torque distribution control strategy, the torque control of the modular motor can be simplified as the current control of each module.

III. SINGLE-PHASE OPEN-CIRCUIT FAULT-TOLERANT STRATEGY FOR MODULAR MOTOR

The single-phase open-circuit fault will occur in one single phase of the motor or one bridge arm of the inverter. The two types of the open-circuit fault can be treated by the same fault-tolerant strategy. So based on the characteristic of the modular motor which is that each module can be regarded as a common three-phase motor, MMF compensation strategy is employed to deal with the single-phase open-circuit fault in one module. When the fault occurs, the amplitude of the resultant fundamental magnetic flux generated by the corresponding module in the air gap decreases and cannot be constant, resulting in a decrease of torque and large torque ripple. Taking phase A_1 in Module 1 open as an example, in order to weaken the bad effect of phase A_1, the currents of phase B_1 and C_1 can be adjusted according to the principle of MMF to compensate for the MMF drop caused by open-circuit fault.

Under normal condition, the fundamental MMF of a three-phase symmetrical winding in a single module is:

$$\begin{aligned} F_{n1} &= f_{A_1} + f_{B_1} + f_{C_1} \\ &= NI_{m1}\cos(\omega_e t)\cos(\theta_s) + NI_{m1}\cos(\omega_e t - \frac{2\pi}{3})\cos(\theta_s - \frac{2\pi}{3}) \\ &\quad + NI_{m1}\cos(\omega_e t - \frac{4\pi}{3})\cos(\theta_s - \frac{4\pi}{3}) \\ &= \frac{3}{2} NI_{m1}\cos(\omega_e t - \theta_s) \\ &= \frac{3}{2} NI_{m1}\cos(\omega_e t)\cos(\theta_s) + \frac{3}{2} NI_{m1}\sin(\omega_e t)\sin(\theta_s) \quad (4) \end{aligned}$$

where N is the number of turns per phase in series; θ_s is the electrical angle between the current position and winding A_1 axis.

When phase A_1 is open, the sum of the MMF generated by the other two phases is:

$$F_{1ph-oc} = Ni_{B_1}\cos(\theta_s - \frac{2\pi}{3}) + Ni_{C_1}\cos(\theta_s - \frac{4\pi}{3}) \quad (5)$$

Thus, we get (6)

$$F_{1ph-oc} = (-\frac{1}{2} i_{B_1} - \frac{1}{2} i_{C_1}) N\cos\theta_s + (\frac{\sqrt{3}}{2} i_{B_1} - \frac{\sqrt{3}}{2} i_{C_1}) N\sin\theta_s \quad (6)$$

where i_{B_1} and i_{C_1} are the currents of phase B_1 and C_1 after the fault occurred, respectively. Assuming that the increase of current will not cause the saturation in the cores, then letting (4) equal to (6), we get:

$$\begin{aligned} i_{B_1} &= \sqrt{3} I_{m1}\cos(\omega_e t - \frac{5\pi}{6}) \\ i_{C_1} &= \sqrt{3} I_{m1}\cos(\omega_e t + \frac{5\pi}{6}) \end{aligned} \quad (7)$$

The zero-sequence current can be given by

$$i_0 = \frac{1}{3}(i_{A_1} + i_{B_1} + i_{C_1}) = -\sqrt{3} I_{m1}\cos(\omega_e t) \quad (8)$$

The faulty structure of Module 1 and its inverter is presented in Fig. 3 (The red lines mean the open-circuit faulty phases

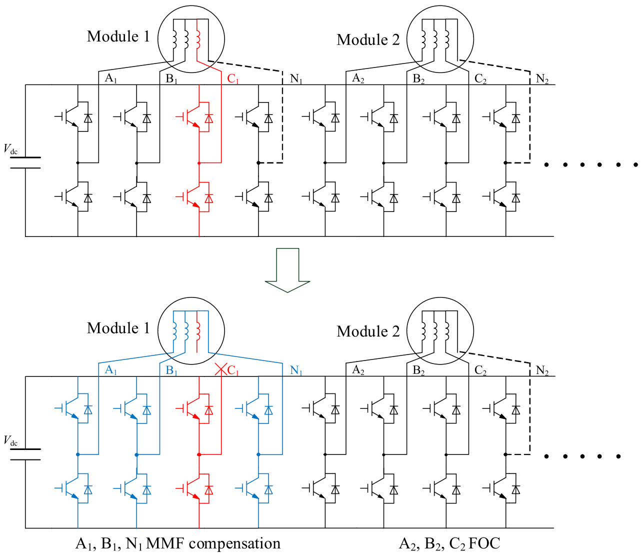

FIGURE 3. The structure of the faulty module under the single-phase open-circuit fault.

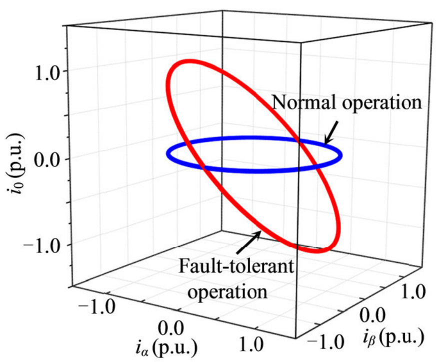

FIGURE 4. The current vectors under normal and fault-tolerant condition.

and the blue lines mean the remaining healthy phases with the proposed fault-tolerant strategy. The meanings of red and blue lines are the same in Fig.5-Fig.10.). The phase A_1 and the corresponding bridge arm have been cut off, and the redundant leg for the neutral point is activated. In this case, the current vector locus is elliptical, but its projection in the α-β plane is a circle (see Fig. 4). This reduces the torque ripple under fault condition and makes the faulty module provide output torque.

From (7), the electrical angle between the currents of B_1 and C_1 is equal to 60 degree. But the amplitude of the currents of the two remaining healthy phases is increased to $\sqrt{3}$ times than the rating value under continuous normal condition, which means the fault module cannot work under the fault-tolerant operation for a long time. The alternative is to decrease the amplitude of the currents of B_1 and C_1 to the rating value, which can be realized by tuning the torque distribution ratio between the fault module and the healthy one. When $i_d = 0$, the ratio of torque to current is constant. The torque distribution ratio between the faulty module and the healthy one is

$$T_{e\_faulty} : T_{e\_healthy} = \frac{1}{\sqrt{3}} : 1 \tag{9}$$

So, the output torque capability of the faulty module drops by 57.7%, but it have ability of the long-time fault-tolerant operation. For the modular motor, the total output torque capability drops by $(n - 0.423)/n$, which is higher than $(n - 1)/n$ of the traditional cutting off strategy.

IV. MULTIPHASE OPEN-CIRCUIT FAULT-TOLERANT STRATEGY FOR MODULAR MOTOR

The modular motor has enormous potential against the multiphase open-circuit fault. The multiphase open-circuit faults in the modular motor are very complex. The faulty modules may consist of not only ones with the single-phase open-circuit fault but also ones with the two-phase open-circuit fault. But the MMF compensation strategy cannot handle the two-phase open-circuit fault in one module, which is not enough as the final open-circuit fault-tolerant strategy of the modular motor. Considering that each module has the same electrical position and the corresponding phase has the same electrical angle in the modular motor, we develop the EOCFTC strategy to make the most of the remaining healthy phases in the faulty modules by winding reconstruction, which can achieve the maximum output torque capability for the modular motor. Because the EOCFTC strategy is a structure-based method by replacing the faulty phases with the healthy phases of the same electrical angle from other modules, the principle will be described below in detail by enumerating multiphase open-circuit faults using structural diagrams.

A. TWO-PHASE OPEN-CIRCUIT FAULT OF THE MODULAR MOTOR

The two-phase open-circuit fault of the modular motor has two cases. The first case is that the two open-circuit faulty phases belong to the same module, such as the phase A_1 and phase C_1 of Module 1 in Fig. 5. In order to reuse the remaining healthy phase B_1, a phase of different electrical angle from a healthy module (like the phase A_2 of Module 2) will be borrowed to form a reconstructed two-phase module. This new module and Module 2 with two healthy phases left can be controlled by the MMF compensation strategy. In particular, phase A_2 of Module 2 should be cut off from the neutral point N_2 and be linked to the neutral point N_1 of Module 1. So, using the proposed strategy, the total output torque capability of the modular motor drops by $(n - 0.846)/n$, which is higher than $(n - 1)/n$ of the traditional cutting off strategy.

The second case is that the two open-circuit faulty phases belong to two difference modules, such as Module 1 and Module 2 in Fig. 6. Then the MMF compensation strategy is employed to process the fault in the two modules. So, the total output torque capability of the modular motor drops by $(n - 0.846)/n$, which is higher than $(n - 2)/n$ of the traditional cutting off strategy.

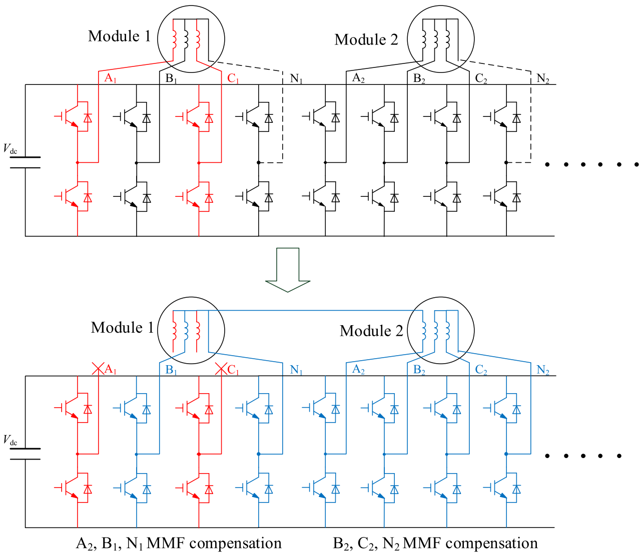

FIGURE 5. **The structure of the faulty module under the two-phase open-circuit fault in the first case.**

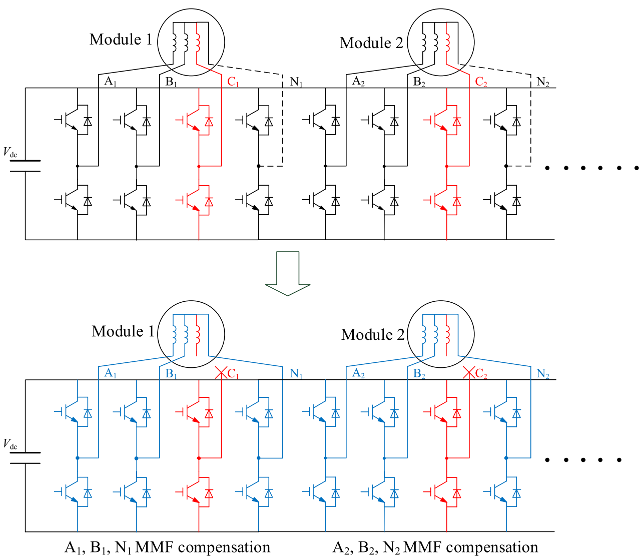

FIGURE 6. **The structure of the faulty modules under the two-phase open-circuit fault in the second case.**

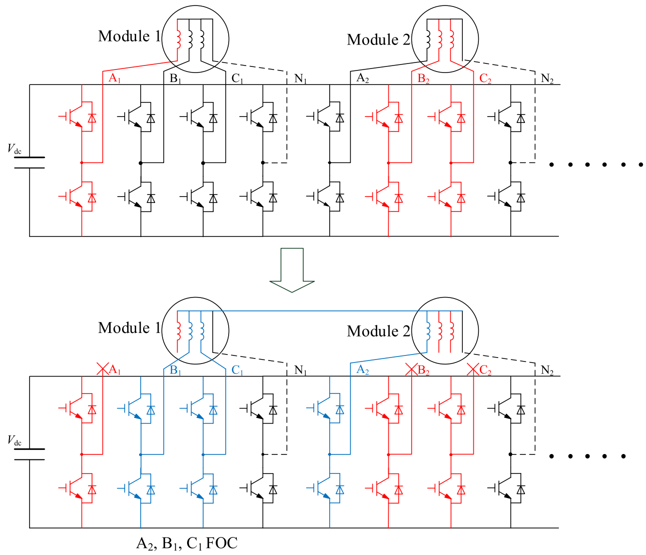

FIGURE 7. **The structure of the faulty modules under the three-phase open-circuit fault in the second case.**

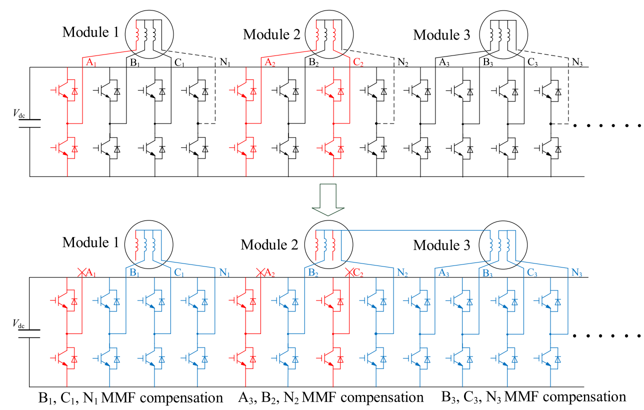

FIGURE 8. **The structure of the faulty modules under the three-phase open-circuit fault in the third case.**

B. THREE-PHASE OPEN-CIRCUIT FAULT OF THE MODULAR MOTOR

The three-phase open-circuit fault of the modular motor has four cases. The first case is that the three open-circuit faulty phases belong to the same module. This module is cut off naturally, which is not meaningful to be studied.

The second case is that the three open-circuit faulty phases belong to two difference modules and meanwhile their electrical angles are different with each other, such as the phase A_1 of Module 1 and phase B_2, C_2 of Module 2 in Fig. 7. The remaining healthy phases of the two modules (phase B_1, C_1 of Module 1 and phase A_2 of Module 2) can be just reconstructed as a full three-phase module. The new module can be operating as a healthy module by employing FOC strategy. Specially, the neutral points of the two faulty modules need to be linked together. So, the total output torque capability of the modular motor drops by $(n-1)/n$, which is higher than $(n-2)/n$ of the traditional cutting off strategy and $(n-1.423)/n$ of the only MMF compensation strategy.

The third case is that the three open-circuit faulty phases also belong to two difference modules but two of them have the same electrical angle, such as the phase A_1 of Module 1 and phase A_2, C_2 of Module 2 in Fig. 8. Module 1 can be directly handled by the MMF compensation strategy. The situation of Module 2 is the same as Module 1 in the first case of the two-phase open-circuit fault in Part A. Thus the same winding reconstruction method can be applied to Module 2 by borrowing the phase A_3 of Module 3, as shown in Fig. 8. In this case, the total output torque capability of the modular motor drops by $(n-1.269)/n$, which is higher than $(n-2)/n$ of the traditional cutting off strategy and $(n-1.423)/n$ of the only MMF compensation strategy.

The forth case is that the three open-circuit faulty phases belong to three difference modules. The three faulty modules

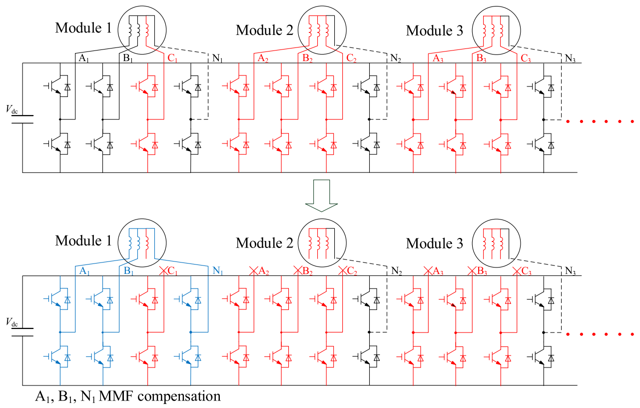

FIGURE 9. The structure of the faulty modules under the extreme multiphase open-circuit fault in the first case.

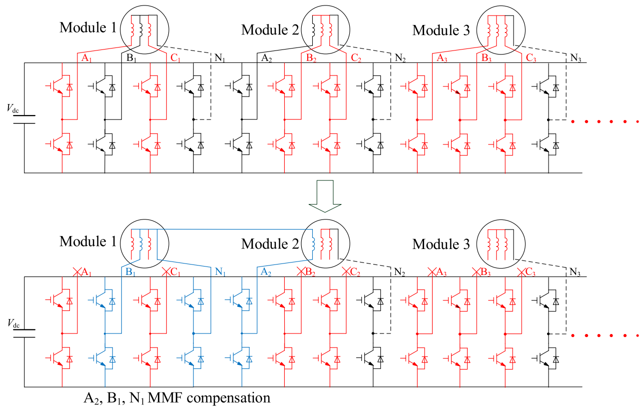

FIGURE 10. The structure of the faulty modules under the extreme multiphase open-circuit fault in the second case.

can be dealt with by the MMF compensation strategy. It is an extension of the second case of the two-phase open-circuit fault in Part A. And the total output torque capability of the modular motor drops by $(n - 1.269)/n$, which is higher than $(n - 3)/n$ of the traditional cutting off strategy.

C. OTHER MULTIPHASE OPEN-CIRCUIT FAULTS OF THE MODULAR MOTOR

Obviously, the processing methods of other multiphase open- circuit faults in the EOCFTC strategy are the same as ones of the two-phase and three-phase open-circuit fault aforementioned. So, there is no need to enumerate all multiphase open-circuit faults in detail. It is worth noting that the EOCFTC strategy can make the most of the remaining healthy phases, which makes the faulty modular motor has the maximum output torque capability under different multiphase open-circuit faults.

The only cases that the faulty modular motor with the EOCFTC strategy cannot operate are that all remaining healthy phases have the same electrical angle. So, the extreme case of multiphase open-circuit faults is that only two healthy phases of different electrical angles in the whole modular motor are left. If the two phases belong to the same module, the fault-tolerant strategy include the MMF compensation only, such as the phase A_1 and B_1 of Module 1 in Fig. 9. If the two phases belong to different modules, the fault-tolerant strategy should combine the MMF compensation with the winding reconstruction, such as the phase A_2 of Module 2 and B_1 of Module 1 in Fig. 10. The total output torque capability of the modular motor drops by $0.577/n$, whereas there is no way to handle this case by the traditional strategy. This shows how strong the fault tolerance of the modular motor with the EOCFTC strategy is under the multiphase open-circuit fault. Table 1 is a summary of all multiphase open-circuit faults and corresponding control strategies (the MMF compensation (MMFC) and the winding reconstruction (WR)), and the FOC strategy for three-phase modules is not listed for simplification.

TABLE 1. Summary of multiphase open-circuit faults with the EOCFTC strategy.

Number of Faulty Phases	Number of Faulty Modules	EXAMPLE	Control Strategy	Torque Capability
1	1	A_1	MMFC	(n-0.423)/n
2	1	A_1, B_1	MMFC+WR	(n-0.846)/n
	2	A_1, A_2	MMFC	(n-0.846)/n
3	1	A_1, B_1, C_1	Cut off	(n-1)/n
	2	A_1, B_2, C_2	WR	(n-1)/n
	2	A_1, A_2, C_2	MMFC+WR	(n-1.269)/n
	3	A_1, A_2, A_3	MMFC	(n-1.269)/n
⋮	⋮	⋮	⋮	⋮
n-2	n-2	A_1, A_2	Cut off	0
	n-2	A_2, B_1	MMFC+WR	0.577/n
	n-1	A_1, B_1	MMFC	0.577/n

V. EXPERIMENTS

An experimental platform for the two-module modular motor is developed to verify the correctness of the proposed theoretical analysis. The experimental platform and the stator of the two-module modular motor are shown in Fig. 11. TMS320F28335 is employed as the microprocessor of the control system, which has enough resources to drive two three-phase modules. The parameters of the modular motor are listed in Table 2. In the modular motor control system, the two modules have one speed controller, which outputs the total torque. Based on the torque distribution strategy, two current controllers handle the d- and q-axis current of each module respectively, where the given d-axis currents are zero.

A. NORMAL OPERATION

In normal operation, the given speed is 500rpm, and the load torque is 3N·m. Specifically the load torque increased from 0 to 3N·m in 2s, but decreases to 0 almost immediately. Other experiments of faulty operation are much the same with this, and the only difference is the value of the load torque. The curves of d- and q-axis currents, and phase currents are illustrated in Fig.12. The two-module modular

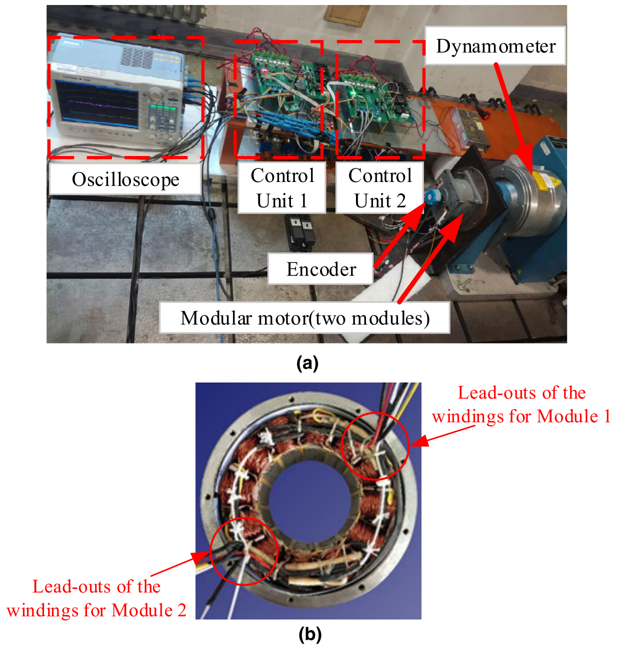

FIGURE 11. The experimental platform: (a) the whole system, (b) the stator of two-module modular motor with 8 poles, 12 slots.

TABLE 2. Modular motor's main parameters.

Parameters	Value
Rated Torque	3N·m
Number of Pole Pairs	4
Phase Winding Resistance	0.5Ω
d-axis inductance	23.8mH
q-axis inductance	42.8mH
PM Flux Linkage	0.072Wb

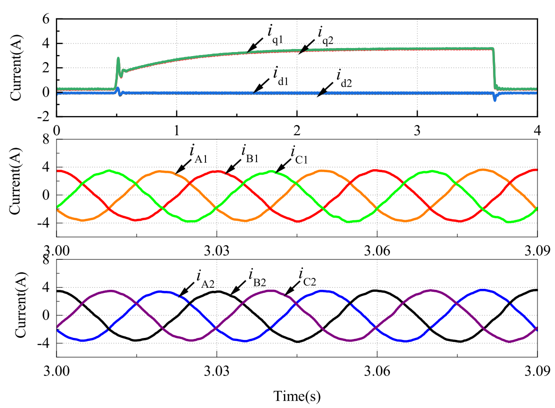

FIGURE 12. The experimental curves under normal operation: d- and q-axis currents of Module 1 and Module 2, phase currents of Module 1 and Module 2.

motor has good static and dynamic performance. The data of q-axis currents and phase currents amplitude are shown in Table 3, which will be the basic values in the next experiments.

TABLE 3. The experimental data under normal operation.

Module Number	Var.	Value	p.u. Value
Module 1	I_q	3.54A	1
	I_m	3.69A	1
	T_e	1.53N·m	1
Module 2	I_q	3.58A	1
	I_m	3.67A	1
	T_e	1.55 N·m	1
Total Motor	T_e	3.08 N·m	1

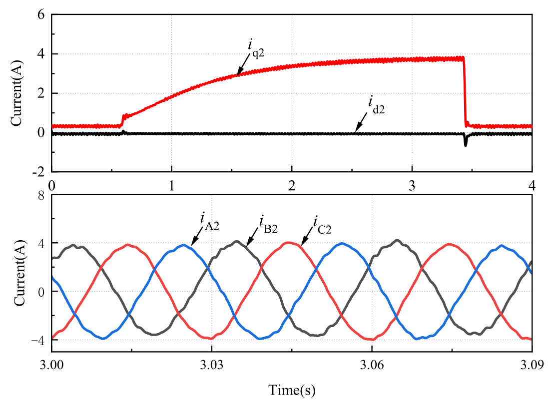

FIGURE 13. The experimental curves under single-phase open-circuit fault using the TOCFTC strategy: d- and q-axis currents, phase currents of Module 2.

B. SINGLE-PHASE OPEN-CIRCUIT FAULT USING THE TOCFTC STRATEGY

If the open-circuit fault (such as C_1) occurs in Module 1, the traditional open-circuit fault-tolerant control (TOCFTC) strategy is to cut off Module 1 for avoiding the large torque ripple. Keeping the amplitude of phase currents of the remaining healthy phases unchanged, the load torque should be adjusted to 1.5N·m. The curves of the d- and q-axis currents, and phase currents are illustrated in Fig. 13, and the data are shown in Table 4. It can be seen that using the traditional strategy the output torque of the modular motor reduces to 0.52 times of that in the normal operation, which is close to the theoretical value 0.5.

C. SINGLE-PHASE OPEN-CIRCUIT FAULT USING THE EOCFTC STRATEGY

The fault case is the same as Part B. The MMF compensation strategy is employed for the fault-tolerant operation of Module 1. According to the above analysis, the torque distribution ratio of Module 1 and Module 2 is 1 : $\sqrt{3}$. Keeping the amplitude of phase currents of the remaining healthy phases unchanged, the load torque should be adjusted to 2.366N·m. The curves and data of the d- and q-axis currents, and phase currents are illustrated in Fig. 14 and Table 5. Because the current vector locus of Module 1 is elliptical as shown in Fig. 4, the phase current of Module 1 has larger error than others. The output torque of the modular motor

TABLE 4. The experimental data under single-phase open-circuit fault using the TOCFTC strategy.

Module Number	Var.	Value	Actual p.u. Value	Theoretical p.u. Value
Module 1	I_q	0	0	0
	I_m	0	0	0
	T_e	0	0	0
Module 2	I_q	3.74A	1.04	1
	I_m	3.98A	1.08	1
	T_e	1.61N·m	1.04	1
Total Motor	T_e	1.61N·m	0.52	0.5

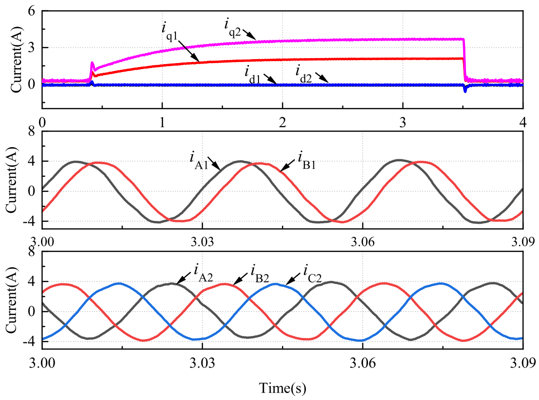

FIGURE 14. The experimental curves under single-phase open-circuit fault using the EOCFTC strategy: *d*- and *q*-axis currents of Module 1 and Module 2, phase currents of Module 1 and Module 2.

TABLE 5. The experimental data under single-phase open-circuit fault using the EOCFTC strategy.

Module Number	Var.	Value	Actual p.u. Value	Theoretical p.u. Value	Error
Module 1	I_q	2.08A	0.587	0.577	1.7%
	I_m	4.09A	1.10	1	10%
	T_e	0.90N·m	0.588	0.577	1.7%
Module 2	I_q	3.68A	1.03	1	3%
	I_m	3.84A	1.05	1	5%
	T_e	1.59N·m	1.03	1	3%
Total Motor	T_e	2.49N·m	0.809	0.788	2.6%

reduces to 0.809 times of that in the normal operation, which is close to the theoretical value 0.788. And compared with the traditional strategy in Part B, the MMF compensation strategy in this case can increase the output torque by 28.9%.

D. TWO-PHASE OPEN-CIRCUIT FAULT USING THE EOCFTC STRATEGY

The two-phase open-circuit fault of the modular motor has two cases according to Part A of Section IV. In the first case, the phase A_1 and C_1 of Module 1 are chosen as the two open-circuit faulty phases. The remaining healthy phase B_1 is reconstructed with the phase A_2 of Module 2 into a two-phase module (Reconstructed Module 1). The MMF compensation

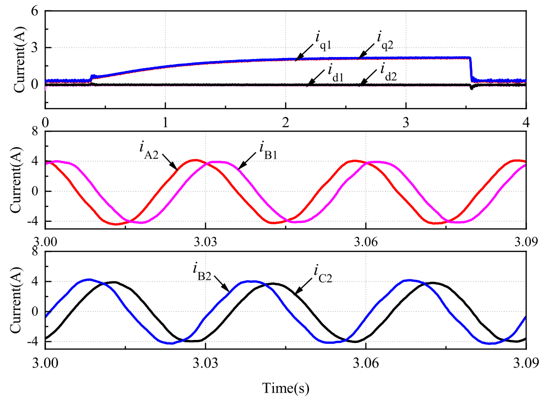

FIGURE 15. The experimental curves under two-phase open-circuit fault using the EOCFTC strategy: *d*- and *q*-axis currents of Module 1 and Module 2, phase currents of Module 1 and Module 2.

TABLE 6. The experimental data under two-phase open-circuit fault using the EOCFTC strategy.

Module Number	Var.	Value	Actual p.u. Value	Theoretical p.u. Value	Error
Rec. Module 1	I_q	2.13A	0.601	0.577	1.7%
	I_m	4.11A	1.119	1	10%
	T_e	0.92N·m	0.601	0.577	1.7%
Rem. Module 2	I_q	2.17A	0.606	0.577	3%
	I_m	4.18A	1.132	1	5%
	T_e	0.93N·m	0.606	0.577	3%
Total Motor	T_e	1.85N·m	0.601	0.577	2.6%

strategy is employed, and the load torque is 1.731N·m. The curves and data of the *d*- and *q*-axis currents, and phase currents are illustrated in Fig. 15 and Table 6. Except for the effects of MMF compensation, the limited manufacturing process and technical level of the modular motor also has effect on the experimental values of the reconstructed Module 1. Meanwhile because the two modules have the same rotor, Module 2 was influenced by Module 1. It can be seen that the EOCFTC strategy with the MMF compensation and winding reconstruction can handle the two-phase open-circuit fault in one module well. The reconstructed module is the similar as the original module, e.g. Reconstructed Module 1 and Remaining Module 2. The output torque of the modular motor reduces to 0.601 times of that in the normal operation, which is close to the theoretical value 0.577. The second case is an extension of the case of the single-phase open-circuit fault in Part C, which is no need for repeating validation.

E. THREE-PHASE OPEN-CIRCUIT FAULT USING THE EOCFTC STRATEGY

For the analysis of the three-phase open-circuit fault of the modular motor in Part B of Section IV, there are four cases. The first one is the same as Part B. The third one is like the combination of Part C and Part D. And the forth one is an extension of Part C. So only the second one need to

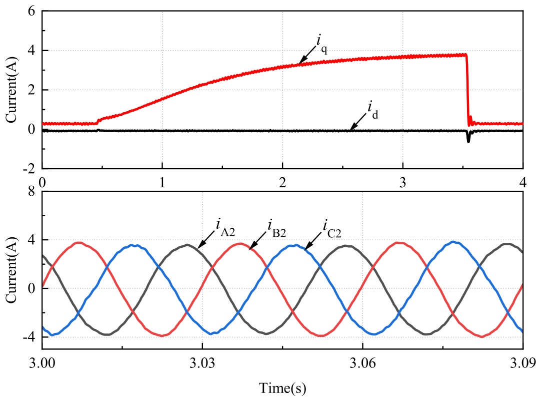

FIGURE 16. The experimental curves under three-phase open-circuit fault using the EOCFTC strategy: *d*- and *q*-axis currents of reconstructed module, phase currents of reconstructed module.

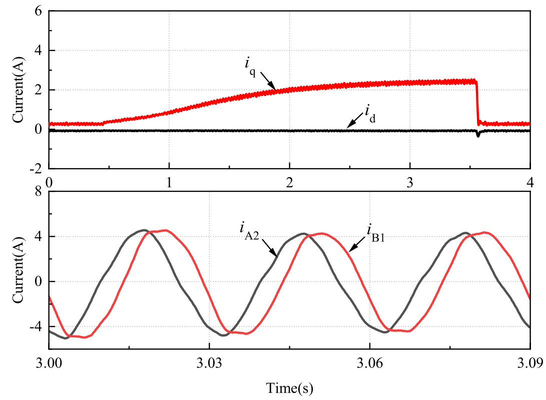

FIGURE 17. The experimental curves under extreme multiphase open-circuit fault using the EOCFTC strategy: *d*- and *q*-axis currents of reconstructed module, phase currents of reconstructed module.

TABLE 7. The experimental data under three -phase open-circuit fault using the EOCFTC strategy.

Module Number	Var.	Value	Actual p.u. Value	Theoretical p.u. Value
Rec. Module	I_q	3.71A	1.04	1
	I_m	3.81A	1.03	1
	T_e	1.60N·m	1.04	1
Total Motor	T_e	1.60N·m	0.52	0.5

TABLE 8. The experimental data under extreme multiphase open-circuit fault Using the EOCFTC strategy.

Module Number	Var.	Value	Actual p.u. Value	Theoretical p.u. Value	Error
Rec. Module	I_q	2.32A	0.655	0.577	13.5%
	I_m	4.41A	1.195	1	19.5%
	T_e	1.00N·m	0.655	0.577	13.5%
Total Motor	T_e	1.00N·m	0.325	0.289	12.4%

be validated in detail. Assuming that the open-circuit fault occur in the phase A1 of Module 1 and phase B2, C2 of Module 2, the remaining healthy phases of the two modules (phase B1, C1 of Module 1 and phase A2 of Module 2) have different electrical angles with each other and can be just reconstructed as a full three-phase module. At this moment, the load torque is 1.5N·m, and the FOC strategy is employed. The curves and data of the *d*- and *q*-axis currents, and phase currents are illustrated in Fig.16 and Table 7. Compared with Part B, the reconstructed three-phase module has similar performance as the original module (Module 2 in Part B), which proves the validity of the winding reconstruction strategy.

F. EXTREME MULTIPHASE OPEN-CIRCUIT FAULT USING THE EOCFTC STRATEGY

Finally, the experiment under the extreme multiphase open-circuit fault of the modular motor is carried out. No matter the two remaining healthy phases belong to the same module or two different modules, the experimental results are similar, which can be concluded from previous experiments. So the main purpose of this part is to show how strong the fault tolerance of the modular motor with the EOCFTC fault-tolerant strategy is under the extreme case of the multiphase open-circuit fault. Assuming that the phase B_1 of Module 1 and A_2 of Module 2 are the only two healthy phases left, the load torque becomes 0.866N·m. The curves and data of the *d*- and *q*-axis currents, and phase currents are illustrated in Fig.17 and Table 8. The main reasons of errors are the effects of MMF compensation and the limited manufacturing process and technical level of the modular motor. The fault modular motor still has the output torque capability. The output torque is up to 0.95N·m which is 0.308 times of that in the normal operation, whereas the output torque by using the traditional strategy is 0.

VI. CONCLUSION

A novel fault-tolerant strategy of the modular motor under open-circuit faults called EOCFTC is proposed in this paper. The remaining healthy phases are reconstructed with a developed winding reconstruction strategy, and then controlled by MMF compensation and FOC strategy. The Experimental results verify the rationality and feasibility of the proposed fault-tolerant strategy on a two-module modular motor.

(1) The EOCFTC strategy can deal with all kinds of open-circuit faults effectively. Even if under the extreme open-circuit fault that only two healthy phases with different electrical angles remain, the faulty modular motor with the EOCFTC strategy still has capability to output constant torque.

(2) The faulty modular motor can achieve maximum output torque capability by making the most of the remaining healthy phases. The faulty system based on the EOCFTC strategy can operate steadily and reliably for a long time under open-circuit faults.

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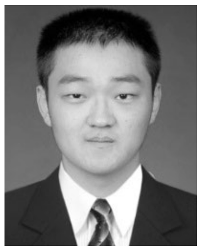

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