Comparative analysis of the operating performance, magnetic field, and temperature rise of the three-phase permanent magnet synchronous motor with or without fault-tolerant control under single-phase open-circuit fault

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Abstract
In the power transmission system, the semiconductor device in the inverter is one of the main fault points. When the open- or short-circuit fault occurs in the semiconductor device, the motor can be turned into the operation with open-phase fault. To take into account the non-ideal factors existing in the calculation, this study establishes a system-level calculation model including the permanent magnet synchronous motor (PMSM), inverter, and different control strategies, which is used to analyse the operating performance of the PMSM with or without fault-tolerant control under single-phase open-circuit fault. In addition, based on the finite element method, the current fault characteristic and the change of the internal magnetic field distribution before and after the fault are studied, and the temperature rise of the PMSM with and without fault-tolerant control is compared. The aim of this study is to compare the operating performance of the three-phase PMSM under two common fault conditions, and quantitatively give the variation range of magnetic flux density and temperature rise. The theoretical analysis in this study is verified by building a systematic experiment platform.

1 | INTRODUCTION

In the electric drive system with the permanent magnet synchronous motor (PMSM), due to the long-term operation, complex working environments, variable working conditions, transport and installation of the equipment, and other unexpected factors, some faults are inevitable. Compared with the motor, the inverter is often more vulnerable [1]. According to statistics, inverter faults are mainly caused by open- and short-circuit faults of semiconductor devices [2]. Short-circuit fault is fatal in the driving system, and it will irreparably damage the semiconductor device and force the system to stop running. Therefore, there are many mature hardware detections and protection devices for preventing the occurrence of the short-circuit fault. Compared with the short-circuit fault, the open-circuit fault will not immediately destroy the semiconductor device and make the system stop running. Since the open-circuit fault is relatively difficult to detect and accounts for a large proportion of the total fault rate, most fault detection and fault-tolerant solutions focus on the open circuit operation of the inverter [3–5].

When the semiconductor device in the inverter is open circuit, the most direct method is to cut off the phase in which it is located, so as to be converted into the operation of the motor with open-phase fault. To improve the control degree of freedom and the fault-tolerant capability of the motor after different faults, the multi-phase motor has become a current hot issue, which is also the main trend of the future development in electric drive systems [6–13]. Reference [6] proposes to inject the fundamental and third-harmonic current components into the non-faulty phase, so that the five-phase PMSM can continue operating stably under single-phase and two-phase open circuit faults. In [7] and [8], the field-oriented control of the five-phase PMSM after open-phase fault is realized by adopting the reduced-order transformation matrix. A new direct torque control for the five-phase induction motor is proposed in [9], which can make the motor to maintain good running performance with the open-phase fault. In [10], a
fault-tolerant control strategy based on genetic algorithm is proposed to improve the average torque of the six-phase PMSM under single-phase open circuit and reduce the torque ripple. In [11], a direct torque control strategy without a position sensor for the six-phase PMSM under two-phase open circuit is proposed. Reference [12] studies the control method of the minimum loss for the six-phase motor in the full torque operating range under two-phase open circuit, and reference [13] comprehensively evaluates the fault-tolerant capability of three kinds of six-phase induction motors (asymmetrical, symmetrical, and dual three-phase). In addition, there are also a lot of research results for the motor with more phases, such as the 9-phase motor and 10-phase motor [14–16].

Although the multi-phase motor has many obvious advantages, the traditional three-phase motor is still widely used in most industrial applications due to its lower cost and mature technology. If the three-leg topology is used to drive three-phase motor, after the single-phase open-circuit fault, the neutral line of the motor needs to be connected to the midpoint of DC link to maintain stable output torque [17]. With this topology, it is necessary to change the connection mode between the motor and the inverter after the motor stops running. In addition, after the motor is restored to operation, its maximum allowable speed is also reduced by half [18], which is undesirable in some situations that require high reliability and performance. Therefore, considering the fault-tolerant scheme, the four-leg driving topology is mostly adopted to increase the redundancy of the system and the diversity of control strategies [19–22]. A distribution strategy of residual phase currents is proposed in [19] for the PMSM under single-phase open circuit. On this basis, reference [20] introduces three-dimensional space vector pulse width modulation (3D-SVPWM) on the α–β frame, so that the motor can be switched from healthy operation to fault-tolerant operation without stopping. In [21] and [22], new transformation matrices are proposed to avoid the tracking problem of sinusoidal current in traditional control methods.

Whether in the three-phase motor system or multi-phase motor system, most of the research focuses on the optimization of control strategies and fault detection of semiconductor devices [23–25]. The existing research results have significantly enhanced the reliability of the motor operation and improved the system performance. However, few studies reported the effect of the single-phase open-circuit fault on the internal physical field of the PMSM. In our previous study [26], the magnetic field and temperature rise in the PMSM under the fault-tolerant mode of the four-leg topology were studied. However, fault detection failure is likely to occur under the harsh operating environment or strong electromagnetic interference, which will not make the PMSM run in the fault-tolerant mode. When the single-phase open-circuit fault occurs in the three-phase drive system, the PMSM will continue running. In this case, the current will be distorted, the torque ripple will increase, and the physical field will also change accordingly. The main motivation of this study is to compare and analyse the operating performance, harmonic variation relationship, magnetic field distribution, and temperature rise of the three-phase PMSM with and without the fault-tolerant control strategy.

No matter in fault-tolerant mode or fault mode, the temperature rise inside the PMSM will change significantly. The temperature change of the PMSM is closely related to the reliability of the system. Excessive winding temperature can accelerate the ageing of the insulating material, which will cause the inter-turn short circuit fault and short circuit fault to the ground. The high temperature in the permanent magnet will reduce the operating performance of the PMSM and even cause irreversible demagnetization. Therefore, this study analyses the temperature field under two operating conditions, which not only quantitatively gives the limit temperature rise of the PMSM in the fault mode, but also provides the theoretical reference for the fault-tolerant PMSM design.

The contribution of this study is mainly reflected in the following aspects. First, considering the harmonic effects of the inverter, a system-level analysis model including the PMSM, external circuit, and with/without the fault-tolerant control strategy under the single-phase open-circuit state is established. The finite element method is used to calculate the model, and the electromagnetic torque, current, and magnetic field changes of the PMSM under different operation modes are given. Second, a three-dimensional global temperature analysis model is constructed to compare the temperature rise of the winding and permanent magnet in different modes. Finally, the results of the theoretical calculation are verified by establishing an experimental platform. The data obtained in this study can provide corresponding references for the PMSM design and thermal management scheme.

2 | CONSTRUCTION OF SYSTEM ANALYSIS MODEL

2.1 | Single-phase open-circuit fault of the PMSM without fault-tolerant method

In most three-phase PMSM systems for industrial applications, rotor field-oriented control is usually used to transform the three-phase current into the two-phase current in a synchronous rotating coordinate system to achieve separate control of torque and flux. The driving topology of the three-phase PMSM is shown in Figure 1.
When one phase of the PMSM is disconnected from the inverter (take the open circuit fault in phase A as an example), according to Kirchhoff’s current law, the sum of the residual two-phase currents of the three-phase PMSM with wye-connected is zero.

\[ i_b + i_c = 0 \]  

where \( i_b \) and \( i_c \) are the currents of phase B and phase C in the three-phase stationary coordinate system. Through coordinate transformations [26, 27], the voltage and current in the \( \alpha–\beta \) frame after the fault can be expressed as:

\[ i_a = i_d \cos \theta_c - i_q \sin \theta_c = 0 \]  

\[ i_b = i_d \sin \theta_c + i_q \cos \theta_c \]  

\[ u_a = \frac{2}{3} \left( u_{ag} - \frac{1}{2} u_{bg} - \frac{1}{2} u_{cg} \right) \]  

\[ u_b = \frac{\sqrt{3}}{3} \left( u_{bg} - u_{cg} \right) \]  

where \( i_a \) and \( i_b \), \( u_a \) and \( u_b \) are the currents and voltages in the two-phase stationary coordinate system, \( i_d \) and \( i_q \) are the currents in the synchronous rotating coordinate system, \( u_{ag} \), \( u_{bg} \) and \( u_{cg} \) are the three-phase voltages relative to the negative bus terminal, respectively, \( \theta_c \) is the angle between the \( d \)-frame and the phase \( A \) winding frame, that is, the rotor position angle of the PMSM. Because the phase \( A \) winding is open, \( u_{ag} \) cannot be determined, so the changes of the current and torque after the fault need to be obtained by \( u_b \) [28]. The voltage of the PMSM in the synchronous rotating coordinate system \( d–q \) frame can be expressed as [29]:

\[ u_d = R_s i_d + \frac{d \Psi_d}{dt} - \alpha \Psi_q \]  

\[ u_q = R_s i_q + \frac{d \Psi_q}{dt} + \alpha \Psi_d \]  

\[ \Psi_d = L_d i_d + \Psi_f \]  

\[ \Psi_q = L_q i_q \]  

where \( u_d \) and \( u_q \), \( \Psi_d \) and \( \Psi_q \) are the voltages and flux linkages in the \( d–q \) frame, \( R_s \) is the stator phase resistance, \( \alpha \) is the electrical angular velocity of the rotor, \( \Psi_f \) is the permanent magnet flux linkage. The prototype studied in this research is a surface-mounted PMSM, so \( L_d = L_q = L \). According to Park transformation and combining with Equations (2)–(9), the \( u_b \) after the fault can be expressed as:

\[ u_b = R_s (i_d \sin \theta_c + i_q \cos \theta_c) + L \left( \frac{di_d}{dt} \sin \theta_c + \frac{di_q}{dt} \cos \theta_c \right) \]

\[ + \alpha \Psi_f \cos \theta_c \]  

\[ + \frac{dp}{dt} = -\frac{R_s}{L} \rho + \frac{1}{L} u_b - \frac{1}{L} \omega \Psi_f \cos \theta_c \]

where \( \rho \) is the stator phase resistance, \( \alpha \) is the electrical angular velocity of the rotor, \( \Psi_f \) is the permanent magnet flux linkage. The prototype studied in this research is a surface-mounted PMSM, so \( L_d = L_q = L \). According to Park transformation and combining with Equations (2)–(9), the \( u_b \) after the fault can be expressed as:

\[ u_b = R_s (i_d \sin \theta_c + i_q \cos \theta_c) + L \left( \frac{di_d}{dt} \sin \theta_c + \frac{di_q}{dt} \cos \theta_c \right) \]

\[ + \alpha \Psi_f \cos \theta_c \]

\[ + \frac{dp}{dt} = -\frac{R_s}{L} \rho + \frac{1}{L} u_b - \frac{1}{L} \omega \Psi_f \cos \theta_c \]

According to Equation (2), a new auxiliary variable \( \rho \) can be defined as [28]:

\[ \rho = \frac{i_d}{\sin \theta_c} - \frac{i_q}{\cos \theta_c} \]  

Bring Equation (11) into Equation (10), the \( i_d \) and \( i_q \) after the fault can be expressed as:

\[ \frac{di_d}{dt} = \frac{dp}{dt} \sin \theta_c + \omega \rho \cos \theta_c \]  

\[ \frac{di_q}{dt} = \frac{dp}{dt} \cos \theta_c - \omega \rho \sin \theta_c \]  

\[ \frac{dp}{dt} = -\frac{R_s}{L} \rho + \frac{1}{L} u_b - \frac{1}{L} \omega \Psi_f \cos \theta_c \]

In the surface-mounted PMSM, the electromagnetic torque is proportional to \( i_q \) and \( \Psi_f \). It can be seen from Equations (10–14) that after phase A is an open circuit, \( \rho \) is a sinusoidal variable, and \( i_d \) and \( i_q \) are no longer the constant DC variables. In this state, the torque of the PMSM will fluctuate periodically, and the harmonic components of the residual two-phase currents will increase significantly.

### 2.2 | Single-phase open-circuit fault of the PMSM with fault-tolerant method

Based on the above analysis, only one-phase current is independent when an open-phase fault occurs, so it is impossible to synthesize a rotating magnetic field with the circular trajectory. To increase the current control degree of freedom, a fourth leg is added and connected to the neutral line of the PMSM. As shown in Figure 1, when phase A is open circuit, a compensation current will flow through the fourth leg to maintain the output torque before the fault.

\[ i_b + i_c + i_n = 0 \]  

where \( i_n \) is the neutral line current. According to Clarke and Park transformations, the expression of the current after the fault-tolerant can be obtained as [26]:

\[ i_b = \sqrt{3} \left( i_q \sin \left( \theta_c + \frac{\pi}{6} \right) - i_d \cos \left( \theta_c + \frac{\pi}{6} \right) \right) \]  

\[ i_c = \sqrt{3} \left( i_q \sin \left( \theta_c - \frac{\pi}{6} \right) - i_d \cos \left( \theta_c - \frac{\pi}{6} \right) \right) \]  

\[ i_n = -3 i_0 = 3 i_d \cos \theta_c - 3 i_q \sin \theta_c \]
varying degrees, which will also increase the burden on the semiconductor device and the temperature rise in the PMSM.

2.3 | Construction of coupling model between PMSM and controller

In this section, the coupling models of the three-phase PMSM with and without fault-tolerant control are constructed, and the two operating conditions are compared in the later section. In terms of the PMSM, the finite element analysis method is adopted to fully consider the non-ideal factors such as the magnetic circuit nonlinearity, cogging effect, and harmonic magnetic field. The analytical equation of the transient electromagnetic field expressed is [26, 30]:

\[
\Omega : \frac{\partial}{\partial x} \left( \frac{1}{\mu} \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\mu} \frac{\partial A}{\partial y} \right) = - \left( J - \sigma \frac{dA}{dt} \right) \quad (19)
\]

\[
\Gamma_1 : A = 0
\]

where \( \Omega \) is the computed region, \( A \) is the magnetic vector potential, \( J \) is the current density, \( \mu \) is the permeability, \( \sigma \) is the conductivity, and \( \Gamma_1 \) is the first boundary condition. To simplify the complexity of the solution process, the boundary equivalent current method is used to model the permanent magnet [26].

\[
\Gamma_2 : \left( \frac{1}{\mu_1} \frac{\partial A}{\partial n} \right) \mid_+ - \left( \frac{1}{\mu_2} \frac{\partial A}{\partial n} \right) \mid_- = J_i \quad (20)
\]

where \( \Gamma_2 \) is used for the side faces of the magnets, \( l \) is the junction between the equivalent surface current layer of the permanent magnet and other materials, \( J_i \) is equivalent surface current density of the permanent magnet, \( \mu_1 \) and \( \mu_2 \) are the permeability of the two mediums on the side faces of the permanent magnet. For calculating and analysing the PMSM and controller as a whole, it is necessary to couple the finite element model with the external circuit. The analysis equation of field-circuit coupling is [31]:

\[
u_s = R_s i_s + L_e \frac{di_s}{dt} + \frac{l_k}{s} \left( \int_{\Omega+} \frac{\partial A}{\partial t} d\Omega - \int_{\Omega-} \frac{\partial A}{\partial t} d\Omega \right) \quad (22)
\]

where \( u_s \) and \( i_s \) are the phase voltage and phase current, respectively, \( L_e \) is the end winding inductance, \( l_k \) is the axial core length, \( s \) is the cross-section area of one turn, \( \Omega+ \) and \( \Omega- \) are the total areas of positively and negatively oriented coil sides of the phase winding in the solution sector, respectively.

In terms of the controller, to compare the changes of torque, current, magnetic field, and temperature rise of the three-phase PMSM with and without the fault-tolerant control, the system calculation model under two control strategies are constructed, respectively. As shown in Figure 2, when there is no fault-tolerant control method, the system includes a speed loop and two current loops, and adopts the 2D-SVPWM, which is the same as the traditional rotor field-oriented control. When considering a fault-tolerant operation, the additional current loop needs to be added to control the neutral line current. In addition, to enable the PMSM to switch from the healthy operation to the fault-tolerant operation without stopping, and the modulation method remains unchanged, the 3D SVPWM in the three-phase stationary coordinate system is used to drive the semiconductor device [26].

Moreover, in the process of electromagnetic calculation of the coupling model, the following assumptions are made.

1. The influence of the displacement current is ignored, and the electromagnetic field is quasi-static; 2. The equivalent surface current method is adopted in the calculation model of the permanent magnet, that is, the equivalent volume current density of the permanent magnet is zero; 3. The influence of temperature on conductivity and magnetic permeability is ignored; and 4. The armature magnetic field is the two-dimensional distributed, and the end effect is considered by the constant end leakage inductance in the external circuit.

3 | ANALYSIS OF PMSM OPERATING PERFORMANCE AND MAGNETIC FIELD

During the running of the PMSM, due to the complex operation environments, variable working conditions, and many uncertain factors, it is likely to interfere with the fault detection signal and even makes the detection system malfunction. When the motor is running under the open-phase state, its current and magnetic field will be distorted, and cause torque ripple. The fault characterization of the PMSM in three states of healthy operation, faulty operation, and fault-tolerant operation will be analysed in detail in this section, and the corresponding comparison will be given. The prototype parameters used in this study are shown in Table 1.

The system model constructed in the previous section is calculated through the finite element method, and the winding currents in three operating states are shown in Figure 3.

It can be observed from Figure 3 that the three-phase winding currents are symmetrical to each other when the PMSM is running under the condition with no faults, and the RMS of the phase current is 4.15 A. After \( T = 0.35 \) s, the phase A winding is disconnected from the inverter, and the current of the phase A is zero. At this time, the winding currents of phase B and phase C are equal in amplitude and opposite in phase, and the maximum value of the winding current is 16.06 A. If the fault-tolerant operation scheme is considered, the sinusoidal compensation current will flow through the neutral line after the phase A is open circuit at \( T = 0.5 \) s, and its maximum value is 18.19 A. In contrast, the increase in the amplitude of the phase B and phase C currents is relatively small, with a maximum value of 10.58 A. It can be seen from the
data comparison that the amplitude of the maximum current flowing through the PMSM and the inverter has increased by about four times in both the fault mode and fault-tolerant mode. Among them, the maximum current in fault-tolerant mode is about 2 A larger than that in fault mode.

The waveform shape of the phase B current is the same as the phase C current under the fault and fault-tolerant state. Therefore, harmonic analysis is performed on the phase B current in three operating states, as shown in Figure 4. It can be observed from Figure 4 that when the motor is switched from the healthy operation to the fault-tolerant operation, the fundamental amplitude of the phase B current increases by 4.3 A, and other harmonic currents are basically unchanged, which is also consistent with the analysis results in Equations (15)–(18). However, when the motor is operating in the fault mode, the amplitudes of the fundamental, third, fifth, and seventh harmonics increase obviously. Among them, the amplitude of the third harmonic is 4.064 A, which also indicates that the operating performance of the PMSM will be significantly reduced. Furthermore, the comparison of the torque under the rated load is shown in Figure 5. It can be seen from Figure 5 that if the fault-tolerant scheme is not adopted after the phase A open circuit, the torque output by the PMSM will oscillate periodically. The torque after the fault fluctuates between 0 and 30.15 N m, and its average value is 11.2 N m, which is close to the rated torque of 12 N m. Compared with the healthy mode, the torque ripple in the fault-tolerant mode is basically unchanged, which shows that the PMSM can still maintain excellent operating performance after the fault.

From the above analysis, it can be seen that whether it is in fault mode or fault-tolerant mode, the winding current will change accordingly, which will affect the armature reaction. Moreover, the PMSM can still continue running with the single-phase open circuit, so it is necessary to compare and analyze the changes in the magnetic field under different operating conditions. A major advantage of the coupling model is that it can accurately analyze the influence of changes in control strategies on the physical field. Based on the system analysis model constructed in Section 2, the calculated magnetic flux density distribution is shown in Figure 6. From the analysis in Figure 6, it can be observed that the maximum value of the magnetic flux density in the fault mode and the fault-tolerant mode is increased by 0.37 and 0.18 T, respectively, compared to the healthy mode. The magnetic flux at the stator

**TABLE 1** Motor parameters

| Items                  | Value            |
|------------------------|------------------|
| Rated power            | 1.5 kW           |
| Rated voltage          | 242 VAC          |
| Rated current          | 4 A              |
| Rated speed            | 1200 r/min       |
| Rated frequency        | 100 Hz           |
| Core length            | 110 mm           |
| Stator outer diameter  | 128 mm           |
| Stator inner diameter  | 80 mm            |
| Rotor outer diameter   | 77.6             |
| Rotor inner diameter   | 21 mm            |
| Moment of inertia      | 0.0035 kg m²     |
According to the analysis in the previous section, the open-phase fault of the PMSM will not only change the operating performance, but also have a more significant impact on the current harmonic content and the magnetic field. The change of current will alter the winding copper loss and rotor eddy current loss, and the change of magnetic field distribution will affect the stator core loss, which will further alter the temperature field in the PMSM. Especially in the fault mode, the motor will continue running with unsatisfactory performance, which will endanger the safety of the system. Therefore, it is very important to analyse and
compare the temperature rise in the PMSM under the open-phase fault.

4.1 Construction of temperature analysis model

The loss in the PMSM mainly includes the winding copper loss, stator core loss, rotor eddy current loss, mechanical loss, and stray loss. The above loss is taken as the heat source, and the steady-state temperature field is calculated. The copper loss, stator core loss, and rotor eddy current loss can be calculated by Equations (23)–(25) [26, 32].

\[
P_{cu} = 3I^2R_c \tag{23}
\]

\[
P_{core} = k_B f B_{m}^2 + k_d f^2 B_{m}^2 + k_d f^{1.5} B_{m}^{1.5} \tag{24}
\]

\[
P_{PM} = \frac{1}{I_c} \int_{T_s}^{T_f} \sum_{n=1}^{m} \Delta T \Delta \sigma_c^{-1} I_c dt \tag{25}
\]

where \(P_{cu} \), \(P_{core} \), and \(P_{PM} \) are the winding loss, stator core loss density, and PM eddy current loss, \(I \) is the phase current, \(k_B \), \(k_d \), and \(k_a \) are the coefficient of hysteresis loss, eddy current loss, and excess loss, \(f \) is the frequency, \(B_m \) is the peak value of the magnetic flux density, \(T_e \) is the cycle of time, \(J_e \) is the current density in each element, \(\Delta \) is the element area, \(\sigma \) is the conductivity of the PM, and \(l_r \) is the rotor axial length. In the calculation process, the mechanical loss and stray loss are considered as 1% of the rated power, respectively. According to the material used in the PMSM and its actual size, a three-dimensional temperature calculation model is constructed, as shown in Figure 7.

On the premise of not affecting the calculation accuracy, the following assumptions are made for reducing the complexity of the calculation process [26].

1. The thermal conductivity of the material is constant and unaffected by external temperature;
2. The influence of thermal radiation on thermal conduction is negligible; and
3. The ambient temperature is constant, and the initial temperature of the PMSM is equal to the ambient temperature.

The three-dimensional steady-state temperature field analysis equation of the PMSM can be expressed as [33]:

\[
\frac{\partial}{\partial x} \left( \lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda_z \frac{\partial T}{\partial z} \right) = -q_v \tag{26}
\]

\[
k \frac{\partial T}{\partial n} \bigg|_{s_1} = 0 \tag{27}
\]

\[
-k \frac{\partial T}{\partial n} \bigg|_{s_2} = k_d (T - T_f) \tag{28}
\]

where \(\lambda_x \), \(\lambda_y \), and \(\lambda_z \) are the thermal conductivity of the material along \(x \), \(y \), and \(z \) directions in the computed region, respectively, \(q_v \) is the sum of the each heat source density, \(k \) is the normal thermal transfer coefficient, \(s_1 \) is the adiabatic boundary surface, \(s_2 \) is the boundary surface of the PMSM heat dissipation, \(k_d \) is the heat dissipation coefficient of \(s_2 \), and \(T_f \) is the ambient temperature. The prototype cooling method in
this study is free cooling, and the heat inside the PMSM is dissipated to the external environment through the case. The heat dissipation coefficient of the case is [34]:

\[
\alpha = 9.73 + 14\varepsilon^{0.62}
\]

(29)

Considering the experimental environment of the tested prototype, \( v = 1 \text{m/s} \) is taken in the temperature model calculation. When the PMSM runs to the rated speed, the Reynolds number in the air-gap is greater than the critical Reynolds number, then the airflow in the air-gap is turbulent. In this situation, the thermal conductivity in the air-gap is [34, 35]:

\[
R_e = \frac{v \delta_g}{\mu_s}
\]

(30)

\[
\lambda_g = 0.0019 \cdot \eta^{-2.9084} \cdot R_e^{0.4614\ln(3.3336\eta)}
\]

(31)

where \( v_{\Delta} \) is the linear velocity of the outer circumferential surface of rotor, \( \delta_g \) is the length of the air-gap, \( \mu_s \) is the kinematic viscosity of air, \( \eta = \frac{R_{\text{rotor}}}{R_{\text{stator}}} \), \( R_{\text{rotor}} \) and \( R_{\text{stator}} \) are the outer diameter of rotor and the inner diameter of stator, respectively. In addition, according to the different materials used in the PMSM, Table 2 shows the thermal conductivity during thermal calculation.

| Items            | Thermal conductivity, W/(m-K) |
|------------------|------------------------------|
| Stator winding   | \( \lambda = 400 \)          |
| Stator core      | \( \lambda = 48, \lambda_y = 48, \lambda_z = 1.7 \) |
| Slot wedge       | \( \lambda = 0.8 \)          |
| Rotor core       | \( \lambda = 48, \lambda_y = 48, \lambda_z = 1.7 \) |
| Permanent magnet | \( \lambda = 7.5 \)          |
| End cover        | \( \lambda = 96 \)           |
| Base             | \( \lambda = 12 \)           |
| Shaft            | \( \lambda = 50.2 \)         |

| TABLE 2 Thermal conductivity of each part of the prototype |

4.2 Temperature analysis

Based on the temperature analysis model constructed above, the computed region is calculated using the finite element method. If the winding temperature is too high, the ageing speed of the insulation material will be accelerated, which will cause the fault of inter-turn short circuit. Excessive permanent magnet temperature will reduce the operating performance of the PMSM and even destroy the motor.

This study focuses on the temperature distribution of the stator and permanent magnets to avoid the above thermal faults. The temperature of the PMSM under the rated operating condition is calculated as shown in Figure 8. It can be observed from Figure 8 that when the prototype is running in the healthy mode, the temperature distribution in the stator winding is uniform, and the maximum temperature of the winding is 83.8°C. The maximum temperature of the permanent magnet is 86.9°C. When phase A is open circuit, the temperature of the three-phase winding will be different because no current flows through the phase A winding. The amplitude of the residual two-phase currents will increase by \( \sqrt{3} \) times under fault-tolerant mode, so the winding temperature will also increase accordingly.

Although there is no copper loss in the phase A winding at this time, the temperature of the phase B and phase C windings will be transferred to the phase A winding. Compared with the healthy mode, the maximum temperature of the winding and the permanent magnet in the fault-tolerant mode is increased by 14.3°C and 12.5°C, respectively. However, the temperature rise in the PMSM will increase significantly in the fault mode. It can be seen from the harmonic decomposition of the current in Figure 4 that the amplitude of the third harmonic current in the fault mode is obviously increased, which will further increase the winding copper loss and the eddy current loss of the permanent magnet. Compared with the healthy mode, the maximum temperature of the winding and the permanent magnet in the fault mode is increased by 35.3°C and 31.3°C, respectively. It can be noticed that the winding temperature of the prototype in the fault mode is 119.1°C, which has reached the maximum allowable temperature of insulation level E. The maximum temperature of the permanent magnet is 118.2°C, which is also very close to the maximum working temperature of the N35H brand. It can be concluded from the above analysis that although the single-phase open-circuit fault will not destroy the PMSM immediately, it will significantly reduce the PMSM performance and is likely to cause other secondary faults due to high temperature.

5 EXPERIMENT ANALYSIS

For verifying the correctness of the theoretical analysis, an experiment platform for prototype and control system is built. Since the fault mode may destroy the prototype and semiconductor devices, the experiment mainly includes the operation of the prototype in the healthy operation and the fault-tolerant operation. As shown in Figure 9, the experiment platform mainly includes power supply, power circuit, drive circuit, microprocessor control unit (MUC), and detection components. The power circuit is a four-leg driving topology, and the model of the semiconductor device is IGBT FF75R12RT4. The MCU is the digital signal processor TMS30F28335, whose main function is to send out driving signals, process detection data, and communicate with the host computer in real time. The detection components mainly include current detection and temperature detection. Among them, the current detection element adopts the Hall current sensor, which is used to feedback the transient current to the MUC, and plays the role of open-phase fault monitoring. The temperature sensor model is PT100; it is installed at the end of the winding, the neutral point, and the
stator tooth top to measure the temperature rise in real time. The tested prototype is connected to a PMSG through a torque-speed sensor. The AC power generated by the PMSG is converted into the DC power through the diode rectification topology, which is consumed on a DC adjustable resistor. In the experiment, the tested prototype is operated at the rated torque by adjusting DC resistance.

In the process of software debugging, the sample rates of the current loop and the speed loop are set to 100 μs and 1 ms, respectively, and the IGBT FF75R12RT4 switching frequency is 10 kHz. When the prototype is running stably under the rated condition, the driving signal for the phase A leg is turned off to simulate the phase A open circuit fault. When the open circuit fault occurs, the reference value of the neutral line current is changed to make the prototype run in the fault-tolerant operation. Figure 10 shows the winding current measured by the oscilloscope and the d–q frame current monitored by the host computer.

It can be seen from the experimental results that when the prototype is running under the rated condition with no faults, the three-phase winding currents are symmetrical to each other, and the current RMS value is about 4.16 A. When the prototype is running in the fault-tolerant operation, the reference value of the d–q frame current do not need to be changed, and the fluctuation of the feedback value is very small. The torque of surface-mount PMSM is proportional to

**FIGURE 8** Temperature distribution in three operating states
the $q$-frame current $i_q$, so it can also be inferred that the torque fluctuation in the fault-tolerant operation can meet the engineering requirements. To compare the temperature rise in the healthy operation and the fault-tolerant operation, the tested prototype is operated continuously for about 2 h in the experiment, and the measured temperature under the thermal steady state is shown in Table 3.

State 1, State 2, and State 3 in Table 3 correspond to the healthy mode with rated load, fault-tolerant mode with rated load, and fault-tolerant mode with 2/3-rated load, respectively. From the data in Table 3, it can be seen that the temperature of the residual two-phase windings and the stator tooth top in the fault-tolerant mode has increased by 13.5°C and 8.9°C, respectively, compared to the healthy mode. The temperature in the neutral point has increased by 16.1°C. The temperature rise of the PMSM in the fault-tolerant mode with 2/3 rated load is close to the temperature rise in the healthy mode with the rated load. The measured current and temperature results are consistent with the calculation results in Sections 3 and 4, which verifies the correctness of the theoretical analysis and the accuracy of the model.

6 | CONCLUSION

In industrial applications, the single-phase open circuit is one of the common faults of the PMSM. This study takes the phase A winding as an example to construct a system calculation model including the PMSM, inverter and different control strategies. The operating performance and internal physical

| Table 3 | Measured temperature results |
|---------|-----------------------------|
|         | State 1  | State 2  | State 3 |
| Phase B | 80.2°C   | 94.1°C   | 81.7°C  |
| Phase C | 79.8°C   | 93.3°C   | 81.2°C  |
| Neutral point | 80.1°C | 96.2°C | 81.9°C |
| Stator tooth top | 77.6°C | 86.5°C | 79.3°C |

FIGURE 9  Experiment platform

FIGURE 10  Measured current result: (a) winding current, (b) $d$-frame current $i_d$, and (c) $q$-frame current $i_q$
field of the PMSM with and without the fault-tolerant control method under single-phase open circuit are studied and compared. Compared with the healthy operation, the amplitude of the fundamental current in the fault-tolerant operation and the fault operation has increased by 1.76 and 1.82 times, respectively. Compared with the fault-tolerant operation, the amplitude of the third harmonic current in the fault mode increases significantly, and the amplitudes of the fifth, seventh, and ninth harmonic currents also increase to varying degrees.

In addition, although the average torque in the fault mode is close to the rated torque, the torque fluctuation range is large, and its maximum value is 2.5 times of the rated torque. When the PMSM is running in the fault operation, the maximum value of the magnetic flux density at the tooth top is 0.37 T larger than that in the healthy mode, which makes the flux saturation easier. The temperature field inside the PMSM changes obviously in both fault-tolerant operation and fault operation. Compared with the healthy operation, the maximum temperature of the permanent magnet has increased by 12.5°C and 31.3°C, respectively. The correctness of the analysis results is verified by building a system experiment platform based on fault-tolerant control. The research results obtained in this study can provide the theoretical reference for the PMSM design and the thermal management of the system.

ACKNOWLEDGEMENT

This study was supported by the Fundamental Research Funds for the Central Universities (Grant no. 2020YJS160).

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How to cite this article: Li W, Tang H, Luo S, Yan X, Wu Z. Comparative analysis of the operating performance, magnetic field, and temperature rise of the three-phase permanent magnet synchronous motor with or without fault-tolerant control under single-phase open-circuit fault. IET Electr. Power Appl. 2021;15:861–872. https://doi.org/10.1049/elp2.12065