Decoupled Speed and Flux Control of a Three-Phase Permanent Magnet Synchronous Motor under an Open-Circuit Fault Using a PR Current Controller

Haneen Ghanayem *,†, Mohammad Alathamneh †,‡ and R. M. Nelms ‡

Abstract: Presented in this article is a method for decoupling the speed and flux control of a three-phase permanent magnet synchronous motor (PMSM) during an open-circuit fault (OCF) using a current controller based on proportional resonant (PR) control techniques. The suggested control approach is relatively simple to implement and maintains good motor operation during the open circuit. PMSM performance under pre-fault, OCF, and post-fault conditions were investigated using Matlab/Simulink and an experimental setup based on a dSPACE DS1104. The conducted investigations provide strong evidence supporting the efficacy and resilience of the suggested control approach during OCF conditions.

Keywords: three-phase PMSM; open-circuit fault; decoupled control; flux control; speed control; PR controller

1. Introduction

Permanent magnet synchronous motors (PMSMs) have gained widespread popularity in various industrial applications due to their straightforward design, high efficiency, compact size, and exceptional reliability [1,2]. Over time, numerous control techniques have been devised to govern the operation of PMSMs. A summary of these control techniques is depicted in Figure 1.

Field-oriented control (FOC) is widely recognized as a prevalent technique in the field [3,4]. FOC involves the transformation of three-phase AC current signals into a two-coordinate system through the utilization of the Clarke transformation. This transformation yields two distinct components: the direct current ($i_d$), responsible for generating the...
magnetic flux, and the quadrature current \(i_q\), used to generate both torque and motor speed. As a result of this decoupling, independent control can be achieved of the PMSM flux and torque [5,6].

Multiple control techniques are frequently utilized in permanent magnet synchronous motors (PMSMs), including direct torque control (DTC). DTC eliminates the need for a speed sensor by directly controlling the speed and torque of the PMSM. Additionally, various other control methods have been devised for PMSMs, including model predictive control (MPC), sliding mode control (SMC), and adaptive control.

In a previous study [7], the authors proposed PMSM control based on field-oriented control (FOC) and DTC with space vector pulse width modulation (SVPWM). While DTC relies on flux and torque estimators, FOC needs a physical sensor to measure motor position in order to control speed and torque precisely. A comparative analysis conducted by [8,9] highlighted the features of FOC and DTC. FOC showcased remarkable speed response capabilities and minimal torque ripple, while DTC effectively mitigated switching frequency. Another study [10] evaluated the performance of PMSM using DTC with an SVPWM inverter, employing estimators of the flux and the torque. The study conducted in [11] explored the application of DTC and a frictional PID controller to achieve speed control of a PMSM. Improved overall performance was achieved through the utilization of model predictive control (MPC) for three-phase PMSM speed control in [12,13]. In [14], satisfactory static and dynamic speed performance was achieved by employing sliding mode control (SMC) for the speed loop and a PI controller for the current controller. Deadbeat control methods were explored for direct torque and flux control in [15–17], while [18] presented deadbeat current and flux vector control for an interior permanent magnet synchronous motor (IPMSM). Model reference adaptive control (MRAC) was proposed for the direct torque and flux control (DTFC) of PMSM in [19]. Additionally, ref. [20] introduced a stator flux linkage adaptive SVM-DTC control method for PMSM, aiming to reduce stator output current and enhance overall motor performance.

In general, faults are becoming a common issue from PMSM operation. PMSM faults can be classified into three main categories: electrical, mechanical, and magnetic faults, as shown in Figure 2 [21,22]. The open-circuit fault (OCF) is the most common type of stator winding fault (SWF) and will be studied in this paper.

![Figure 2. Fault types for PMSM.](image)

Reference [23] presents a comprehensive investigation into the operational characteristics of an interior permanent magnet synchronous motor (IP-MSM) under diverse fault conditions. This study explores the performance of the motor employing both maximum torque per ampere (MTPA) and flux weakening control strategies. The fault scenarios examined encompass transistor switch-on failure, single-phase open circuits, uncontrolled generation, and single-phase and three-phase short circuits. In a previous study [24], the
authors conducted a comparative analysis of the three-phase PMSM under two different conditions: one with fault tolerant control (FTC) and the other without, specifically focusing on the single-phase open-circuit fault scenario. An open-circuit fault scenario of a five-phase fault-tolerant permanent magnet motor (FTPM) using the remedial field-oriented control (RFOC) method was studied in [25]. A dual three-phase permanent magnet synchronous motor (DT-PMSM) under open-circuit fault conditions using a genetic algorithm (GAS) was studied in [26]. In [27], single-phase open circuit conditions of a five-phase PMSM using the fault-tolerant SVPWM control method was presented. Improved performance of the five-phase PMSM under an open-circuit fault using a fault-tolerant controller was proposed in [28,29]. In [30], an enhanced fault-tolerant model for predictive current control with continued modulation under open-circuit fault conditions was studied. The introduced approach enhanced both the operational performance and the robustness of the system. In [31], open-circuit fault diagnosis based on model predictive current control (MPCC) for three-phase PMSM drives was proposed. The OCF was detected and located effectively. Moreover, the proposed method showed robustness against operating point variation. Fault tolerance control of three-phase PMSM under open-circuit fault based on deadbeat-direct torque and flux control (DB-DTFC) was investigated in [32]. However, in the proposed method, the utilization of stator flux and current observers was necessary. In [33], two distinct MPC approaches were presented for regulating the surface-mounted PMSM drive in a three-phase system experiencing an OCF condition. The first MPC was used for normal operation, while the second MPC was designed for post-fault operation.

The loss of a single phase in a three-phase motor can result in current distortion, torque fluctuations, mechanical vibrations, and increased stress on the motor. Therefore, it is essential to ensure uninterrupted operation, improve reliability, and ensure the resilience of the drive system in the event of an open-circuit fault. This paper introduces a novel approach for handling open-circuit faults in three-phase PMSMs. The proposed method utilizes decoupled speed and flux controllers alongside a proportional–resonant (PR) current controller. To generate the $d$-axis and $q$-axis reference currents, separate controllers for flux and speed were employed. Additionally, a PR controller was employed to regulate the $dq$-axis currents and generate corresponding reference voltages. The proposed control method was simulated and implemented in an experimental test during three scenarios: pre-fault, during, and post-fault conditions. An encoder was used to measure the speed and the angular position of the motor. In addition, simple calculations based on stator currents were used to calculate the actual flux and torque. Consequently, the need for flux and torque observers is eliminated, leading to a reduction in the overall complexity of the control system.

This work introduces several innovative contributions, which are summarized as follows:

- Guarantee the continuous operation of the motor and enhance the reliability of the drive system against the open-circuit fault.
- Strong robustness control under flux change, speed change, and load conditions under OCF operation.
- Independent control of flux and speed is achieved during OCF conditions.
- Simple control method, no speed/position estimators are required, no PLL is required, and no need to design flux/torque observers.

The structure of this article is as follows: The introduction and literature review are presented in Section 1. The mathematical model of the three-phase PMSM is discussed in Section 2. Section 3 focuses on the open-circuit fault of the PMSM. The proposed control method is outlined in Section 4. Section 5 presents the simulation and experimental results, specifically aimed at validating the effectiveness of the proposed control method under OCF conditions. Finally, Section 6 presents the conclusions drawn from this study.
2. Mathematical Model

The mathematical representation of the PMSM can be described in either the abc-domain or the dq-domain. However, due to its simplicity, the dq-model is widely used in motor control. The stator voltages in the dq-axis are given in Equations (1) and (2).

\[ V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \]  \hspace{1cm} (1)

\[ V_q = R_s i_q + L_q \frac{di_q}{dt} - \omega_r (L_d i_d + \psi_m) \]  \hspace{1cm} (2)

where \( V_d \) represents the stator voltage of the PMSM in the \( d \)-axis, and \( V_q \) represents the stator voltage of the PMSM in the \( q \)-axis, \( R_s \) is the PMSM phase resistance, \( i_d \) is the motor current \( d \)-axis component, \( i_q \) is the motor current \( q \)-axis component, \( L_d \) is the PMSM \( d \)-axis inductance, \( L_q \) is the PMSM \( q \)-axis inductance, \( \omega_r \) is the electrical rotor speed, and \( \psi_m \) is the permanent magnetic flux linkage.

The flux of the PMSM in the \( dq \)-reference frame can be presented in Equations (3) and (4), while Equation (5) describes permanent magnet flux linkage.

\[ \psi_{sd} = L_d i_d + \psi_m \] \hspace{1cm} (3)

\[ \psi_{sq} = L_q i_q \] \hspace{1cm} (4)

\[ \psi_m = \frac{1}{\sqrt{3}} K_e \frac{60}{1000\pi} \] \hspace{1cm} (5)

where \( \psi_{sd} \) denotes the \( d \)-axis stator flux linkage, \( \psi_{sq} \) represents the \( q \)-axis stator flux linkage, and \( k_e \) denotes the voltage constant specific to the PMSM.

The electromagnetic torque can be written as in Equation (6). For surface-mounted PMSM, \( L_d = L_q \) then, Equation (7) can be deduced. Equation (8) describes the rotor’s mechanical speed.

\[ T_e = \frac{3}{2} p (\psi_m i_q + (L_d - L_q) i_d i_q) \] \hspace{1cm} (6)

\[ T_e = \frac{3}{2} p (\psi_m i_q) = K_i i_q \] \hspace{1cm} (7)

\[ \omega_m = \omega_e \frac{2}{p} \] \hspace{1cm} (8)

where \( T_e \) is the electromagnetic torque, \( p \) is the number of pole pairs, \( k_i \) is the torque constant, \( \omega_e \) is the electrical speed, \( \omega_m \) is the mechanical speed.

Clarke and Park transformations are commonly used in PMSM control [34]. The Park transformation is applied to convert the components of a three-phase quantity in the abc domain into a two-axis system in the rotating reference frame (dq) as shown in Equation (9). In addition, the voltages and currents can be converted from \( dq0 \) reference frame into \( \alpha \beta \), as shown in Equation (10).

\[
\begin{bmatrix}
  f_d \\
  f_q \\
  f_0 
\end{bmatrix}
= \frac{2}{3} \begin{bmatrix}
  \sin(\theta) & \sin(\theta - 120) & \sin(\theta + 120) \\
  \cos(\theta) & \cos(\theta - 120) & \cos(\theta + 120) \\
  \frac{1}{2} & \frac{1}{2} & \frac{1}{2} 
\end{bmatrix}
\begin{bmatrix}
  f_\alpha \\
  f_\beta \\
  f_\gamma 
\end{bmatrix}
\] \hspace{1cm} (9)

\[
\begin{bmatrix}
  f_\alpha \\
  f_\beta \\
  f_\gamma 
\end{bmatrix}
= \begin{bmatrix}
  \sin(\theta) & \cos(\theta) & 1 \\
  \sin(\theta - 120) & \cos(\theta - 120) & 1 \\
  \sin(\theta + 120) & \cos(\theta + 120) & 1 
\end{bmatrix}
\begin{bmatrix}
  f_d \\
  f_q \\
  f_0 
\end{bmatrix}
\] \hspace{1cm} (10)
3. Open-Circuit Fault of PMSM

The open-circuit fault is considered the most common type of electrical fault that occurs in a PMSM. The OCF can be single-phase or multiple-phase but, in this article, single-phase open circuit faults will be considered.

When the OCF occurs, the current of the two remaining phases will be increased and distorted, which causes overheating of the motor windings and may cause mechanical damage. This mechanical damage can stress the motor or disrupt the motor’s continuity. In addition, the motor will operate at lower speed with increased torque ripple [23]. The effect of the OCF on the motor and its performance becomes a serious issue, which poses a challenge for motor control.

Under normal operation, the system is balanced, and the sum of the three-phase currents \( i_{abc} \) is zero. The phase currents and back electromotive force \( e_{abc} \) in the three-phase stationary reference frame are described in Equations (11) and (12), respectively.

\[
\begin{align*}
\{i_a & = I_{m} \sin(\theta) \\
    i_b & = I_{m} \sin(\theta - \frac{2\pi}{3}) \\
    i_c & = I_{m} \sin(\theta + \frac{2\pi}{3})
\}
\]

\[
\begin{align*}
\{e_a & = E_{m} \sin(\theta) \\
    e_b & = E_{m} \sin(\theta - \frac{2\pi}{3}) \\
    e_c & = E_{m} \sin(\theta + \frac{2\pi}{3})
\}
\]

However, when OCF occurs, in this article at phase A, no current will flow in phase A, and the sum of the currents will no longer be zero [24]. Therefore, the sum of the currents is shown in Equation (13).

\[
i_{\text{sum}} = i_b + i_c
\]

The construction of the three-phase PMSM drive with phase A open circuit is as shown in Figure 3.

![Figure 3. Topology of three-phase PMSM system under OCF.](image)

When OCF occurs in the same leg (\( T_1 \) and \( T_2 \)), the current in the corresponding phase (phase A) will drop to zero. The phase angles of the current in phases B and C are opposite while the current amplitude is increased by \( \sqrt{3} \), as shown in Equation (14) [35].

\[
\begin{align*}
i_a & = 0 \\
    i_b & = \sqrt{3} I_{m} [\sin(\theta - \frac{2\pi}{3}) + \frac{1}{2} \sin(\theta)] \\
    i_c & = \sqrt{3} I_{m} [\sin(\theta + \frac{2\pi}{3}) + \frac{1}{2} \sin(\theta)]
\}
\]
4. Proposed Control Method

The field-oriented control (FOC) technique is widely utilized in PMSM control due to its simplicity and reliability. The FOC technique enables the independent control of flux and torque in the PMSM, allowing for separate controllers to achieve precise speed and flux control.

Under OCF conditions, the current phase angle and magnitude will be different than in pre-fault conditions, which makes the system unbalanced. Hence, the PR control method is proposed to control the current under the OCF condition.

The actual speed of the motor and the angular position are measured directly from an encoder. The reference speed ($\omega^*$) is compared with its actual value ($\omega$) through a PI controller, generating a reference torque ($T^*$), and then generating the $q$-axis reference current ($i_q^*$). The $d$-axis reference current ($i_d^*$) deviates from zero, and likewise, $\phi_d$ differs from $\phi_m$. To regulate the flux of the PMSM, a proposed flux controller is implemented. The actual flux ($\phi_d$) is compared with the reference flux ($\phi_d^*$) through a separate PI controller, generating $i_d^*$.

The stator currents of the PMSM ($i_{abc}$) are used to calculate the feedback signal for flux and torque, as described in Equations (3) and (7), respectively. However, an $abc$-to-$dq$ transformation is required. The PR control method is applied to the inner current loop to control the current of the motor as well as generate the reference voltages. However, a $dq$-to-$\alpha\beta$ transformation is required.

Figure 4 illustrates the block diagram of the proposed decoupled controller, which effectively integrates speed and flux control with PR control methodology while accounting for the OCF scenario.

![Figure 4. The proposed control method under OCF.](image)

4.1. Speed/Flux Control Design

The speed and flux controllers are both based on the PI controller and are designed using the Ziegler–Nichol’s (ZN) method in [36,37]. The transfer function of the PI-controller is described by Equation (15), whereas the adjustment of the PI-gains is achieved by satisfying Equations (16) and (17).

\[
G_{PI}(s) = K_p + \frac{K_i}{s} \tag{15}
\]

\[
K_p = 0.45 K_{cr} \tag{16}
\]

\[
K_i = \frac{1.2 K_p}{P_{cr}} \tag{17}
\]
4.2. PR Current Controller Design

In this article, the PR controller serves to regulate the current of the PMSM, offering rapid response, accurate regulation, and diminished steady-state error as its prominent features. The transfer function of the PR controller is as described in Equation (18).

\[ G_{PR}(s) = K_p + K_r \frac{s}{s^2 + \omega^2} \]  

\[ (18) \]

\( K_p \) is proportional gain, \( K_r \) is resonant control gain, and \( \omega \) is resonant frequency.

The resonant frequency is chosen at \( \omega = 377 \text{ rad/s} \).

The PR controller aims to reduce the error between the measured current and the reference current in the PMSM system. \( K_p \) and \( K_r \) are tuned as described in [38,39], as follows:

- Initially, \( K_r \) is set to zero.
- Gradually, \( K_p \) is increased until stable oscillation occurs in the error waveform and this happened at \( K_{Pcr} \).
- Then, \( K_p = 0.45K_{Pcr} \).
- \( K_r \) is adjusted until zero steady-state error is achieved.
- Choosing \( K_r \) depends on the desired overshoot and settling time. A higher value of \( K_r \) can decrease both the settling time and steady-state error; however, it can also result in increased overshoot. Therefore, selecting appropriate gains involves finding a balance between minimizing steady-state error and controlling overshoot.

5. Evaluation and Validation

5.1. Simulation Results

To verify the performance of the proposed control method, a three-phase PMSM is built using Matlab/Simulink. The Simulink model of the three-phase PMSM, incorporating decoupled controllers for speed and flux based on the PR control method during OCF conditions, is depicted in Figure 5. Additionally, Table 1 provides the motor’s parameters.

![Figure 5. Simulink model of the proposed control method under OCF.](image_url)
Table 1. The parameters of the PMSM.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>200 W</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>42 V</td>
</tr>
<tr>
<td>Max speed</td>
<td>3000 RPM</td>
</tr>
<tr>
<td>Voltage constant</td>
<td>9.5 V/Krpm</td>
</tr>
<tr>
<td>Resistance (L-L)</td>
<td>0.4 Ohms</td>
</tr>
<tr>
<td>Inductance (L-L)</td>
<td>540 μH</td>
</tr>
<tr>
<td>Pole-pairs number</td>
<td>4</td>
</tr>
<tr>
<td>Magnetic flux linkage</td>
<td>0.01309 Wb</td>
</tr>
</tbody>
</table>

The simulation model was run using Matlab/Simulink for 3 s. The motor was run in pre-fault condition first with 500 rpm reference speed, 0.5 Wb reference flux, and 0.1 N·m load torque. The open-circuit fault occurred at \( t = 1.5 \) s and cleared at \( t = 2 \) s. At \( t = 1.8 \) s, the load torque during the fault condition was adjusted to 0.25 N·m. The performance of the PMSM during the open-circuit fault (OCF) can be observed in Figure 6.

Figure 6a shows the speed of the PMSM during pre-fault, OCF, and post-fault operations. It can be seen that there is a good match between the actual and reference speed of the PMSM during the pre-fault and post-fault conditions. During the faulty operation, the speed dropped slightly to 495 rpm. Subsequently, the load torque is augmented to 0.25 N·m, resulting in a slight additional decrease in the speed value. However, the motor still spins with almost the same reference even under the OCF and the load change. This observation validates the resilience of the suggested control approach in mitigating OCF impact and load disturbances. The currents of the PMSM are as shown in Figure 6b. Under OCF, \( i_a \) dropped to zero, while \( i_b \) and \( i_c \) are distorted and increased as described by Equation (14). Figure 6c depicts the torque response during the three operations. It can be seen that, during a pre-fault operation, the load torque and the motor torque are equal (0.1 N·m). The torque fluctuates under the fault condition and with load changes. Then, it stabilizes when the motor switches to post-fault operation. As shown in Figure 6d, the flux controller has satisfactory independent control. The flux controller tracks the reference value correctly. The OCF causes a small fluctuation in the flux response. In addition, changing the load torque has a very slight effect on the flux response. After the fault is cleared, the flux gradually returns to its original value. Since \( i_d \) is related to the flux and \( i_q \) is related to the torque, as described in Equations (3) and (7), the response of \( i_d \) and \( i_q \) will be similar to flux and torque, respectively, with different gains, as shown in Figure 6e.

![Figure 6a](image)

![Figure 6b](image)

Figure 6. Cont.
5.2. Experimental Results

The performance of the proposed control method under the OCF was verified using an experimental platform, as depicted in Figure 7. The three-phase inverter was connected to the three-phase PMSM. A DC source was used to feed the inverter with 42 V. The dSPACE DS1104 was used to implement the algorithm. The motor speed and the angular position were obtained from an encoder. The sampling frequency and pulse width modulation switching frequency were set to 10 kHz. The table provided (Table 1) outlines the motor specifications along with the controller gains for speed, flux, and currents. Additionally, the PR controller gains are specifically assigned as $K_p = 0.5$ and $K_r = 32$. 

Figure 6. Simulation results under, pre-fault, OCF, and post-fault condition. (a) Motor speed. (b) Stator currents. (c) Torque. (d) Motor flux. (e) dq-axis currents.

Figure 7. Experimental platform.
The motor was run in pre-fault operation first, OCF, and post-fault operation, respectively. Figure 8 shows the experimental results based on the proposed control method.

(a)

(b)

(c)

Figure 8. Cont.
Figure 8. Experimental results under, pre-fault, OCF, and post-fault condition. (a) Motor speed. (b) Stator currents. (c) Torque. (d) Motor flux. (e) d-axis currents. (f) q-axis current.
The motor is operating at 500 rpm reference speed, 0.1 N·m. load torque, and 0.5 Wb reference flux. The OCF occurs at $t = 5.65$ s by disconnecting phase A. Then, the fault is cleared at $t = 11.23$ s. Figure 8a shows the speed performance of the PMSM during pre-fault, OCF, and post-fault operations. It can be seen that the actual speed and the reference speed are almost equal during the three operations. During the OCF, the ripple in the speed is slightly increased. Meanwhile, the motor still performs well. After clearing the fault, the motor gradually returns to normal operation. In Figure 8b, the stator currents of the motor are presented. At $t = 5.65$ s, the current in phase A will drop to zero while the currents in phases B and C are increased and distorted. However, in this work, a current saturation is added to protect the motor. After the fault is cleared, the current is the same as in a pre-fault operation. Figure 8c presents the torque response during the three operations. It can be seen that the motor torque is equal to the applied load torque. During the OCF operation, the torque ripple is increased very slightly to 0.20 N·m, which means that the motor with the proposed control method has high reliability and robustness against faults. Figure 8d displays the flux performance, illustrating that the flux controller accurately follows the reference value throughout all three operations. Even though the OCF causes some oscillation in the flux response, it still remains the same as the reference value. Figure 8e,f show the responses of $i_d$ and $i_q$, respectively. The response of $i_d$ is similar to the flux response, and the $i_q$ response is similar to the torque response.

Decoupled Control Case Study

To validate the proposed control method under the OCF, additional hardware experiments were conducted. The motor operated at a pre-fault condition with a reference speed of 2000 rpm and a reference flux of 0.5 Wb. The OCF occurred at $t = 4.95$ s. Then, the speed was changed during the OCF to 2300 rpm at $t = 9.7$ s. Furthermore, the flux is changed during the OCF operation from 0.5 Wb to 0.9 Wb at $t = 14.42$ s. Then, the fault is cleared at $t = 20.65$ s. Figure 9 illustrates the changes in flux and speed during the OCF operation. Notably, the speed adjustment had no impact on the flux, and vice versa, indicating the successful achievement of independent control over flux and speed in the OCF scenario. Therefore, the proposed decoupled speed/flux control method exhibits high efficacy and robustness in managing the PMSM during OCF.

![Figure 9](image_url)

Figure 9. Cont.
This study highlighted that the loss of one phase in a three-phase motor can result in current distortion, torque fluctuation, mechanical vibration, and increased stress on the motor. To tackle the aforementioned challenges, a control approach was devised that utilizes decoupled controllers for speed and flux, complemented by a current controller employing proportional–resonant (PR) techniques. The $d$-axis and $q$-axis reference currents were generated using individual controllers, while the $dq$-axis currents were regulated and reference voltages were produced through a PR controller. The effectiveness of the proposed method was demonstrated through simulations and experimental tests under different fault conditions. Notably, the control system’s complexity was reduced by eliminating the need for flux and torque observers, enhancing its practical applicability. These novel contributions enhance the understanding and potential applications of the research in the field.

This study encountered several limitations during the hardware experiments conducted. The accuracy of the measurements was affected by sensor error and noise, resulting in significant fluctuations in speed measurements, as well as the calculation of flux and torque. The experiment utilized a DC generator as the load, with torque control achieved through the dSPACE DS1104 and an inverter. Lastly, it is important to mention that the current control during the hardware experiments was constrained within the range of $(-5 \text{ A, } 5 \text{ A})$. Potential future research utilizing the proposed method may explore fault tolerance and fault detection techniques, along with incorporating sensorless control, within the same scenarios.

6. Conclusions

This article presents a novel approach for handling open-circuit fault conditions in a three-phase PMSM. The proposed method utilizes a decoupled speed and flux controller in conjunction with a proportional–resonant control strategy. Separate controllers are used for the speed and the flux. A PR control method is used for the current controller. The performance of the PMSM is evaluated under pre-fault, OCF, and post-fault conditions. Simulation and experiments were conducted to support the proposed control method.
The simulation and experimental results show the good and stable performance of the PMSM during the OCF condition. In addition, independent control of flux and speed was achieved. The speed and flux controllers were able to track their reference values even under OCF operation. Hence, the motor still spins at almost the same speed with slightly smaller torque ripples. Additionally, the effectiveness and robust performance of the proposed control method under OCF operation have been successfully validated. Moreover, the method demonstrates its resilience to load disturbances, further affirming its efficacy in maintaining motor performance despite load variations during OCF conditions.

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