High-Resistance Connection Diagnosis in Five-Phase PMSMs Based on the Method of Magnetic Field Pendulous Oscillation and Symmetrical Components

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High-Resistance Connection Diagnosis in Five-Phase PMSMs Based on the Method of Magnetic Field Pendulous Oscillation and Symmetrical Components

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Abstract:
An online approach for diagnosing high-resistance connection (HRC) faults in five-phase permanent magnet synchronous motor drives is presented in this article. The development of this approach is based on a so-called “magnetic field pendulous oscillation (MFPO)” technique and symmetrical components method. Under HRC fault condition, a “swing-like” MFPO phenomenon is observed compared to the healthy condition. Furthermore, with the extracted current features in symmetrical components domain, different HRC fault types are successfully identified and distinguished. These fault types include single-phase faults, e.g., HRC fault in phase-A; two-phase nonadjacent faults, e.g., HRC fault in phase-A&C; and two-phase adjacent faults, e.g., HRC fault in phase-A&B. Meanwhile, the localization of the faulty phase/phases is also accomplished, and the fault severity is estimated. In this approach, only sensing of the phase currents is needed. Hence, the implementation cost is very low since the sensory data of the currents are typically already available in the closed-loop vector-controlled drives for control purpose and no additional sensors or related signal conditioning circuits are required. The effectiveness of the presented diagnostic approach is verified by simulations and experimental results.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i_{ab,cd,e}$</td>
<td>Phase currents in $abcde$ reference frame.</td>
</tr>
<tr>
<td>$i_{a,b,c,d,e}$</td>
<td>Phasor vector of phase currents.</td>
</tr>
<tr>
<td>$i_{d1,q1}$</td>
<td>$d$- and $q$-axis currents in $d1$-$q1$ reference frame.</td>
</tr>
<tr>
<td>$i_{d3,q3}$</td>
<td>$d$- and $q$-axis currents in $d3$-$q3$ reference frame.</td>
</tr>
<tr>
<td>$i_{p1}$</td>
<td>Phasor vector of positive sequence 1.</td>
</tr>
<tr>
<td>$i_{p2}$</td>
<td>Phasor vector of positive sequence 2.</td>
</tr>
<tr>
<td>$i_{n1}$</td>
<td>Phasor vector of negative sequence 1.</td>
</tr>
<tr>
<td>$i_{n2}$</td>
<td>Phasor vector of negative sequence 2.</td>
</tr>
<tr>
<td>$i_0$</td>
<td>Phasor vector of zero sequence.</td>
</tr>
<tr>
<td>$I_{a,b,c,d,e}$</td>
<td>Magnitude of $i_{a,b,c,d,e}$.</td>
</tr>
<tr>
<td>$I_m$</td>
<td>Root-mean-square value of phase current.</td>
</tr>
<tr>
<td>$I_{P1,P2,N1,N2}$</td>
<td>Magnitude of $i_{P1,P2,N1,N2}$.</td>
</tr>
<tr>
<td>$I_s$</td>
<td>Current space-vector.</td>
</tr>
<tr>
<td>$\angle I_s$</td>
<td>Current space-vector phase angle.</td>
</tr>
<tr>
<td>$m_{ij}$</td>
<td>Regression coefficients, $i = 0, 1, 2; j = 0, 1, 2$.</td>
</tr>
<tr>
<td>$n_{ij}$</td>
<td>Regression coefficients, $i = 0, 1, 2; j = 0, 1, 2$.</td>
</tr>
<tr>
<td>$p$</td>
<td>Number of rotor pole pairs.</td>
</tr>
<tr>
<td>$R_{add}$</td>
<td>Additional resistance.</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Phase resistance.</td>
</tr>
<tr>
<td>$T_e$</td>
<td>Electromagnetic torque.</td>
</tr>
<tr>
<td>$V_{a,b,c,d,e}$</td>
<td>Phase voltages in $abcde$ reference frame.</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Voltage space-vector.</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Phase-shift coefficient, $\alpha = \exp(j2\pi/5)$.</td>
</tr>
<tr>
<td>$\beta_a$</td>
<td>Phase angle of faulted phase-A current.</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Phase angle of magnetic field pendulous oscillation (MFPO) angular position waveform.</td>
</tr>
<tr>
<td>$\delta$</td>
<td>MFPO angular position.</td>
</tr>
<tr>
<td>$\Delta\delta_s$</td>
<td>Magnitude of MFPO angular position waveform.</td>
</tr>
</tbody>
</table>
SECTION I. Introduction

Permanent magnet synchronous motors (PMSMs) have been extensively used in high-performance applications due to their advantages of high torque/power density, high efficiency, high power factor, etc. [1], [2]. Compared to conventional three-phase counterparts, multiphase (>3) PMSM drive systems exhibit lower torque ripple, reduced power per phase, and improved fault-tolerance capability [3]. However, multiphase PMSMs are not immune to all electrical faults/failures. Among these failures, high-resistance connection (HRC) fault is a common and progressive fault, especially in multiphase motor-drive systems, which may be caused by manufacturing imperfections, thermal cycling, damage of the contact surfaces due to corrosion, pitting, or contamination [4]. HRC fault can lead to unbalanced currents and voltages, increased torque pulsation, increased losses and heat, and even more serious failures may occur if the propagation of this fault cannot be prevented at an incipient stage [5]. Hence, expedient diagnosis of HRC fault is essential, especially in safety-critical applications, e.g., electric vehicles, ship propulsion, and aircraft. Accordingly, the diagnosis of HRC fault for a five-phase PMSM drive system is investigated in this article.

HRC fault diagnosis was preliminarily attempted by using voltage drop measurement [6] and infrared thermography methods [7]. The former method is implemented by comparing the voltage drop in each phase of the motor using a voltmeter, whereas the infrared thermography method indicates HRC faults by detecting the hot spots in drive components. However, it is difficult to comprehensively and quantitatively evaluate the HRC fault using either of the two aforementioned methods, since their measurement errors are typically high and hence false alarms are inevitable.

By contrast, the main theory behind the modern diagnostic methods of HRC fault is to monitor the asymmetry of the system using signal-processing-based techniques. For example, an automatic HRC fault diagnostic method for a three-phase induction machine based on the high-frequency signal injection strategy is presented in [8]. With the signatures obtained by measuring the phase currents and the voltage in the machine neutral point, the HRC fault is detected using only one additional voltage sensor. The main limitation of this offline method is that it can only be implemented when the machine is at standstill. Building upon the work in [8], an improved strategy for online HRC fault diagnosis is presented in [9], in which a dc signal instead of high-frequency ac signal is injected into the \( \delta \)-axis of the investigated induction machine during its normal operation. By measuring the resulting dc component in phase currents, the HRC fault is detected and isolated. Another signal injection method for HRC fault diagnosis is presented in [10]. In this method, a dc flux linkage bias is injected into the flux control loop of the direct-torque control system. Then, the resistance deviations are calculated from an established binary linear equation group. It should be noted that the increased losses associated with these signal injection strategies are the main limitations.
In order to mitigate the limitation of the signal injection-based methods mentioned above, several noninvasive diagnostic methods are developed. For example, the signature of the negative-sequence component in the stator currents provided by proportional–integral (PI) regulators is used to detect the HRC fault for a three-phase induction machine in [11] and a seven-phase induction machine in [12]. Besides, an HRC detection method based on multiple reference frame controllers for a seven-phase induction machine is presented in [13]. It was found that inverse current components in the \(\alpha_3 - \beta_3\) and \(\alpha_5 - \beta_5\) reference frames are produced by the unbalance due to the HRC fault, which are normally absent under healthy condition. Based on the loci of the current space-vectors in the aforementioned reference frames, the HRC fault is detected and the faulty phase is identified. However, the detection algorithm becomes much more complex if the fault affects more than one phase at the same time.

In addition, an online approach for diagnosing HRC fault using a zero-sequence current component (ZSCC) method is developed for a three-phase PMSM in [14]. In this method, the faulty phase is identified by the angle differences between the ZSCC and stator currents. The main limitation of this method is that only delta-connected rather than star-connected winding PMSM drive system is investigated in this work. In [15], the amplitude and phase angle of zero-sequence voltage component (ZSVC) are utilized as HRC fault indicators for a three-phase star-connected winding PMSM. Then, this method is extended to be used for the HRC fault diagnosis for a nine-phase flux-switching PM machine in [16]. In [17], by utilizing both the fundamental and high-frequency components of ZSVC, not only HRC fault but also interturn fault is detected and classified for a nine-phase interior PMSM drive system. Furthermore, the effectiveness and flexibility of the ZSVC method are also validated for a brushless dc motor whose back-electromotive force and current waveforms are trapezoidal and square, respectively, rather than sinusoidal as those in induction machines and PMSMs [18]. However, an accessible neutral point of the electric machine, as well as an additional resistance network and a voltage sensor, is necessary in these ZSVC-based methods as shown in [15]–[18], which may not be available in most industrial applications.

Differing from previous work in the literature, this article brings new contributions by presenting an online HRC fault diagnostic approach for a five-phase PMSM, which is fed by a closed-loop vector-controlled drive. This approach is accomplished by the combination of a so-called “magnetic field pendulous oscillation (MFPO)” technique and a symmetrical components method. With the unique extracted features from the MFPO waveforms and the symmetrical components, HRC faults are detected and differentiated from the healthy condition. Then, various HRC fault types are identified and distinguished. These fault types include 1) single-phase (SP) faults, e.g., HRC fault in phase-A, 2) two-phase nonadjacent (TPN) faults, e.g., HRC fault in phase-A&C, and 3) two-phase adjacent (TPA) faults, e.g., HRC fault in phase-A&B. Furthermore, the faulty phase/phases are localized. Moreover, the HRC fault severity is accurately estimated. The implementation cost of this approach is very low, since only sensing of the four phase currents is needed for the five-phase PMSM drive system, whereas these currents are typically already available in the closed-loop vector-controlled drive for control purpose. As a result, no additional sensors or related signal conditioning circuits are needed. The rest of this article is organized as follows. The MFPO phenomenon caused by HRC fault is demonstrated in Section II. In Section III, the presented HRC diagnostic approach and its associated techniques are introduced in detail. Section IV is dedicated to the experimental validation. Finally, Section V concludes this article.

SECTION II. MFPO Phenomenon Due to HRC Fault

The investigated five-phase PMSM drive system is schematically depicted in Fig. 1, whereas the specifications of the system are listed in Table I. This is a surface-mounted PMSM with ungrounded star-connected windings, which is fed by a closed-loop vector-controlled drive. Since the PM flux linkage \(ind_3 – q_3\) reference frame is very small compared to that in \(d_1 – q_1\) reference frame (see Table I), the average torque generated
in $d_3-q_3$ reference frame is negligible compared to that in $d_1-q_1$ reference frame. Hence, only the currents in $d_1-q_1$ reference frame are taken into consideration in this article, and the reference values of $i_{d3}$ and $i_{q3}$ are set as zero in Fig. 1 [19], [20]. It should be noted that to guarantee that both switches in an inverter leg never conduct simultaneously, a small time delay of 2 $\mu$s is added to the gate signal of the turning-on device for handling the dead times and nonideal characteristics of the power inverter [21]. It should also be noted that the HRC fault is modeled by adding an additional resistance $R_{add}$, which is in series connection with a phase winding. The nominal additional resistance $R_{add}$ is set as 0.8 $\Omega$, which is close to the phase resistance [15], [22].

**Fig. 1.** Block diagram of the five-phase PMSM drive system.

**TABLE I** Specific Parameters of the Investigated PMSM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter (mm)</td>
<td>225</td>
</tr>
<tr>
<td>Stack length (mm)</td>
<td>31</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>40</td>
</tr>
<tr>
<td>Number of rotor poles</td>
<td>44</td>
</tr>
<tr>
<td>Rated speed (r/min)</td>
<td>100</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>110/3</td>
</tr>
<tr>
<td>Supply voltage (VDC)</td>
<td>50</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>4.7</td>
</tr>
<tr>
<td>Rated torque (Nm)</td>
<td>18</td>
</tr>
<tr>
<td>Rated power (W)</td>
<td>188.5</td>
</tr>
<tr>
<td>PM flux linkage in $d_1-q_1$ reference frame (Wb)</td>
<td>0.037</td>
</tr>
<tr>
<td>d-axis inductance in $d_1-q_1$ reference frame (mH)</td>
<td>0.85</td>
</tr>
<tr>
<td>q-axis inductance in $d_1-q_1$ reference frame (mH)</td>
<td>0.87</td>
</tr>
<tr>
<td>PM flux linkage in $d_3-q_3$ reference frame (Wb)</td>
<td>0.001</td>
</tr>
<tr>
<td>d-axis inductance in $d_3-q_3$ reference frame (mH)</td>
<td>0.85</td>
</tr>
<tr>
<td>q-axis inductance in $d_3-q_3$ reference frame (mH)</td>
<td>0.88</td>
</tr>
<tr>
<td>Phase resistance (ohm)</td>
<td>0.67</td>
</tr>
</tbody>
</table>

**A. MFPO Phenomenon**

The voltage equation of the five-phase motor-drive system can be expressed as follows:

$$[V_{a,b,c,d,e}] = R_s \cdot [i_{a,b,c,d,e}] + d[\psi_{a,b,c,d,e}]/dt.$$  (1)

Under healthy condition, the five phases are ideally symmetrical. Hence, the phase currents are sinusoidal and sequentially shifted by 72 electrical degrees ($2\pi/5$) from phase-A to phase-E as follows:
where $h$ takes 1, 2, 3, 4, and 5 corresponding to the phase sequence for $i_a, i_b, i_c, i_d,$ and $i_e$, respectively.

According to (2), the current space-vector $I_s$ can be expressed as

$$I_s(t) = 2/5 \cdot [i_a(t) + \alpha \cdot i_b(t) + \alpha^2 \cdot i_c(t) + \alpha^3 \cdot i_d(t) + \alpha^4 \cdot i_e(t)] = I_m \cdot e^{j\omega_s t}.$$  

(3)

Hence, the motor is controlled in such a way that $I_s$ is the only nonnull current space-vector, which rotates counter clockwise (CCW) at synchronous speed. The same conclusion can also be drawn to other electrical quantity space-vectors, including voltage space-vector $V_s$ and flux linkage space-vector $\psi_s$. The average torque of the PMSM can be expressed as follows:

$$T_e = 5/2 \cdot P \cdot (\psi_s \times I_s).$$  

(4)

By contrast, under faulty condition (taking an HRC fault in phase-A as an example), assuming that the motor is with an open-loop control scheme since analyzing such control scheme is the starting point for understanding the behavior of the motor with the complex closed-loop vector-controlled strategy adopted in this article, the faulty phase current $i_a$ would be distorted. The phase currents in (2) are represented as follows:

$$
\begin{align*}
    i_a &= \sqrt{2} \cdot I_m' \cdot \cos(\omega_s t + \beta_a') \\
    i_b &= \sqrt{2} \cdot I_m \cdot \cos(\omega_s t - 2\pi/5); i_c &= \sqrt{2} \cdot I_m \cdot \cos(\omega_s t - 4\pi/5) \\
    i_d &= \sqrt{2} \cdot I_m \cdot \cos(\omega_s t - 6\pi/5); i_e &= \sqrt{2} \cdot I_m \cdot \cos(\omega_s t - 8\pi/5)
\end{align*}
$$  

(5)

According to the multiphase space-vector transformations in [12] and [13], a backward component appears in the current space-vector. More specifically, the current space-vector under HRC fault condition, $I'_s$, can be rewritten as linear combinations of a forward vector $I'_f$, which rotates CCW at synchronous speed $\omega_s$ and a backward vector $I'_b$, which rotates also at synchronous speed but in clockwise direction, $-\omega_s$, as expressed as follows:

$$
\begin{align*}
    \vec{I}'_s &= I'_f \cdot e^{j\omega_s t} + I'_b \cdot e^{-j\omega_s t} \\
    &= (I'_f + I'_b \cdot e^{-j2\omega_s t}) \cdot e^{j\omega_s t} = I'_f + I'_b.
\end{align*}
$$  

(6)
Referring to (4), the resultant current space-vector $\vec{I}'_s$ would lead to a reduced output torque with high torque ripple. As the PMSM is fed by a closed-loop vector-controlled drive, the compensation action of the drive would try to maintain the output torque and mitigate the torque ripple by adjusting the voltage space-vector so as to increase the magnitude of the forward current space-vector $I'_f$ and reduce the magnitude of the backward current space-vector $I'_b$. As a result, the voltage space-vector $\vec{V}'_s$ and the resultant flux-linkage space-vector $\vec{\psi}'_s$ would also consist of a forward component, $\vec{V}'_f$ and $\vec{\psi}'_f$, and a backward component, $\vec{V}'_b$ and $\vec{\psi}'_b$, as expressed as follows [23], [24]:

$$\vec{V}'_s = \vec{V}'_f + \vec{V}'_b = V'_f \cdot e^{j\omega_s t} + V'_b \cdot e^{-j\omega_s t} = (V'_f + V'_b \cdot e^{-j2\omega_s t}) \cdot e^{j\omega_s t}$$

$$\vec{\psi}'_s = \vec{\psi}'_f + \vec{\psi}'_b = \psi'_f \cdot e^{j\omega_s t} + \psi'_b \cdot e^{-j\omega_s t} = (\psi'_f + \psi'_b \cdot e^{-j2\omega_s t}) \cdot e^{j\omega_s t}.$$  

(7)(8)

The aforementioned compensation action cannot fully cancel the backward current space-vector in (6) based on the traditional PI regulators used in the drive, and hence the resultant current space-vector under steady-state operating condition can also be formulated as expressed in (6) [12].

The loci of the current, voltage, and flux-linkage space-vectors in case of an HRC fault are depicted in Fig. 2. As can be seen, under healthy condition, only forward components exist for all the electrical quantity space-vectors, which rotates CCW at synchronous speed $\omega_s$. By contrast, under faulty condition, the asymmetry in the stator windings due to an HRC fault would disturb the air-gap magnetic field, which results in the showing-up of the backward components for all the electrical quantity space-vectors including the current, voltage, and flux-linkage space-vectors. In other words, due to the occurrence of an HRC fault, the resultant air-gap magnetic field orientation oscillates around the original magnetic axis under healthy condition in subsequent leading and lagging manners, whereas the original magnetic axis rotates at synchronous speed. This phenomenon takes place in a continuously alternating or “swing-like” pendulous manner, namely the so-called “MFPO” phenomenon.

![Fig. 2. Loci of space-vectors of the PMSM drive system under HRC fault condition.](image-url)
The original concept of the MFPO is introduced in [25] and [26] and this phenomenon has been previously used to detect the interturn fault in [27] and broken rotor bar fault in [28] for three-phase induction motors, as well as open-phase fault in [29] for five-phase PMSMs. In the previous works, the time-domain values of stator voltages and currents are used to generate the corresponding space-vectors and the oscillation of the angle between the voltage space-vector and the current space-vector is adopted as the fault indicator [25]–[28]. In this way, at least four voltage sensors and four current sensors are needed for the five-phase PMSM drive system investigated in this article. By contrast, a phase-locked loop (PLL) technique is used in [29] to reduce the implementation cost, but an additional speed sensor is required in the PLL circuit. In order to further reduce the implementation cost and the physical volume of the diagnostic approach, the MFPO technique is redeveloped and improved by combining with the symmetrical components method. As a result, only sensing of the four phase currents is needed to implement the HRC fault diagnostic approach, whereas these currents are typically already available in the closed-loop vector-controlled drive for control purpose. Hence, no additional sensors or related signal conditioning circuits are needed in this approach.

B. Symmetrical Components in Five-Phase Systems

The symmetrical components theory is traditionally used for the analysis of unbalances in the electrical power system [30]. It has been attempted to be used in the diagnosis of interturn faults, but mainly focused on three-phase induction motors [31], [32]. Differing from the symmetrical components in three-phase systems, there are five phase sequences for a five-phase system as depicted in Fig. 3, including positive sequence 1 \([A\rightarrow B\rightarrow C \rightarrow D\rightarrow E, \text{see Fig. 3(a)}]\), positive sequence 2 \([A\rightarrow C\rightarrow E\rightarrow B\rightarrow D, \text{see Fig. 3(b)}]\), negative sequence 1 \([A\rightarrow E\rightarrow D\rightarrow C\rightarrow B, \text{see Fig. 3(c)}]\), negative sequence 2 \([A\rightarrow D\rightarrow B\rightarrow E\rightarrow C, \text{see Fig. 3(d)}]\), and zero sequence \([\text{see Fig. 3(e)}]\) [33]. The five sequence components can be calculated as follows:

\[
\begin{bmatrix}
i_{p1} \\
i_{p2} \\
i_{N1} \\
i_{N1} \\
i_0
\end{bmatrix} = \frac{1}{5}
\begin{bmatrix}
1 & \alpha & \alpha^2 & \alpha^3 & \alpha^4 \\
1 & \alpha^3 & \alpha & \alpha^4 & \alpha^2 \\
1 & \alpha^4 & \alpha^3 & \alpha^2 & \alpha \\
1 & \alpha^2 & \alpha^4 & \alpha & \alpha^3 \\
1 & 1 & 1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_d
\end{bmatrix}.
\]  

(9)
For example, the positive sequence 1 phasor vector \( i_{P1} \) is calculated as follows:

\[
i_{P1} = \frac{1}{5} \cdot (i_a + \alpha \cdot i_b + \alpha^2 \cdot i_c + \alpha^3 \cdot i_d + \alpha^4 \cdot i_e)
\]

\[
= \frac{1}{5} \cdot (I_a \angle \varphi_a + \alpha \cdot I_b \angle \varphi_b + \alpha^2 \cdot I_c \angle \varphi_c + \alpha^3 \cdot I_d \angle \varphi_d + \alpha^4 \cdot I_e \angle \varphi_e)
\]

\[
= I_{P1} \angle \theta_{P1}.
\]

(10)

Similarly, the magnitude values of the positive sequence 2 phasor vector, the negative sequence 1 phasor vector, and the negative sequence 2 phasor vector, \( I_{P2}, I_{N1}, \) and \( I_{N2} \), as well as their corresponding phase angles, \( \theta_{P2}, \theta_{N1}, \) and \( \theta_{N2} \), can also be calculated by (9). The difference between the calculations of the positive sequence 1 phasor vector \( i_{P1} \) in (10) and the current space-vector \( i_s \) in (3) should be noted. It should be also noted that the zero sequence component is always null and hence this component is not taken into account in this article, i.e., \( \sum(i_a + i_b + i_c + i_d + i_e) = 0 \), due to the ungrounded star-connected winding configuration of the PMSM.

The positive sequence 1 current profiles under both healthy and HRC fault conditions are shown in Fig. 4. As can be seen, the positive sequence 1 currents under both healthy and HRC fault conditions are the same, which indicates that the positive sequence 1 phasor vector \( i_{P1} \) would not be affected by any oscillation caused by an HRC fault. This is due to the compensation action of the closed-loop vector-controlled drive. Hence, the positive sequence 1 phasor vector \( i_{P1} \) will always coincide/overlap with the axis of the forward current space-vector \( i_f' \) in the space-vector diagram (see Fig. 2). Accordingly, the positive sequence 1 phasor vector \( i_{P1} \) can be used as a reference, which is consistently rotating CCW with a speed equal to the synchronous speed. Hence, the aforementioned MFPO phenomenon can be monitored by the MFPO angular position, which is defined as the
phase shift of the current space-vector $\vec{I_s}$ with respect to the positive sequence 1 phasor vector $i_{p1}$, as shown in Fig. 2, which can be expressed as follows:

$$\delta(t) = \angle I_s(t) - \theta_{p1}(t).$$

(11)

**SECTION III. HRC Fault Diagnosis Based on MFPO Technique and Symmetrical Components Method**

The purpose of the presented diagnostic approach is to achieve the following features.

1. Detection of the HRC fault relative to a healthy condition.
2. Distinction of different HRC fault types. As mentioned in [14] and [22], the most common HRC fault occurs in only one phase. Even so, the fault in two phases is also taken into account for the completeness of this article. As a result, three different HRC fault types are investigated in this article. These fault types include a) SP faults, e.g., HRC fault in phase-A, b) TPN faults, e.g., HRC fault in phase-A&C, and c) TPA faults, e.g., HRC fault in phase-A&B.
3. Localization of faulty phase/phases.
4. Estimation of HRC fault severity.

**A. Detection of HRC Fault Relative to Healthy Condition**

Under healthy condition, since the five-phase currents, $i_a$, $i_b$, $i_c$, $i_d$, and $i_e$, are symmetrical, the positive sequence 1 phasor vector $i_{p1}$ is calculated as $I_m \cdot e^{j\omega t}$ according to (9), whereas the positive sequence 2 phasor vector $i_{p2}$, the negative sequence 1 phasor vector $i_{n1}$, and the negative sequence 2 phasor vector $i_{n2}$ will be zero.

By contrast, under faulty condition, the magnitude values of positive sequence 2 phasor vector, the negative sequence 1 phasor vector, and the negative sequence 2 phasor vector, $I_{p2}$, $I_{n1}$, and $I_{n2}$, respectively, will be a nonzero constant value under steady-state operating condition after an HRC fault. Hence, a detection indicator $\xi$ is defined as the ratio of the sum of $I_{p2}$ and $I_{n2}$ to $I_{p1}$, which is expressed as follows:
\[ \xi = \frac{(I_{P2} + I_{N2})}{I_{P1}}. \]  

(12)

Accordingly, during the detection process, an HRC fault can be alarmed when the detection indicator \( \xi \) is larger than a preset threshold.

B. Distinction of Different HRC Fault Types

The ratio of the magnitude of the positive sequence 2 phasor vector \( I_{P2} \) to the magnitude of the negative sequence 2 phasor vector \( I_{N2} \) is defined as the “fault type indicator,” as follows:

\[ \lambda = \frac{I_{P2}}{I_{N2}}. \]  

(13)

The results of the fault type indicator \( \lambda \) are shown in Fig. 5. The fault cases with \( R_{\text{add}} = 0.4 \, \Omega, 0.8 \, \Omega \) (approximately equal to the rated resistance), and 1.6 \( \Omega \) are included. As can be seen, for all the fault scenarios in SP faults, the fault type indicator \( \lambda \) is always approximately equal to one, i.e., \( \lambda \approx 1 \), no matter what the fault severity is, \( R_{\text{add}} = 0.4 \, \Omega \) [see the left part in Fig. 5(a)], 0.8 \( \Omega \) [see the middle part in Fig. 5(a)], or 1.6 \( \Omega \) [see the right part in Fig. 5(a)]. For TPN faults, the fault type indicator \( \lambda \) is larger than one, i.e., \( \lambda > 1 \). For TPA faults, the fault type indicator \( \lambda \) is smaller than one, i.e., \( \lambda < 1 \). Hence, the fault type indicator \( \lambda \) provides good information for distinguishing the HRC fault types.
C. Localization of Faulty Phase/Phases

Under faulty condition, the phase angle of the positive sequence 1 phasor vector $\theta_{P1}$ is not affected by any oscillations caused by the HRC fault, whereas the current space-vector $I_s'$ is resolved into two components, i.e., the forward component $I_f'$ and the backward component $I_b'$. Both the two components rotate at synchronous speed $\omega_s$ but in opposite direction to each other. In other words, the backward component $I_b'$ is rotating $-2\omega_s$ with respect to the forward component $I_f'$ [see (6)]. Hence, under faulty condition, the MFPO angular position in (11) would be oscillating with a frequency equal to twice the synchronous frequency, which can be rewritten as follows:

$$\delta(t) = \Delta\delta_s \cdot \cos (2\omega_s \cdot t).$$

(14)
The simulated MFPO angular position waveforms under healthy condition and under HRC fault conditions ($R_{\text{add}} = 0.8 \, \Omega$) are shown in Fig. 6. As can be seen, under healthy condition, the MFPO angular position stays almost zero [see Fig. 6(a)]. By contrast, under HRC fault conditions, “swing-like” shaped MFPO angular position waveforms appear [see Fig. 6(b)–(d)]. It is interesting to note that there are two periods in these MFPO angular position waveforms in one electrical cycle under HRC fault conditions, which confirms the second-harmonic nature of the MFPO phenomenon as previously shown in (14). Moreover, for each type of the HRC faults, e.g., SP faults in Fig. 6(a), there is a 72° phase shift between two adjacent faults of the five fault scenarios. More specifically, the MFPO angular position waveform of the HRC fault in phase-A is 72° leading compared to that of the HRC fault in phase-B, whereas the MFPO angular position waveform of the HRC fault in phase-B is 72° leading compared to that of the HRC fault in phase-C, and so forth. The same rule was shown in the results of the other two HRC fault types, i.e., the TPN faults in Fig. 6(b) and the TPA faults in Fig. 6(c). In addition, with respect to the second-harmonic nature of the MFPO phenomenon and the fact that the positive sequence 1 phasor vector $iP_1$ would not be affected by any oscillations caused by an HRC fault, the angle difference between the half phase angle of the MFPO angular position waveform, $\gamma/2$, and the phase angle of the positive sequence 1 phasor vector $\theta_{P_1}$ will be constant for each fault case, whereas it will be significantly different (72° difference in sequence is expected) if the HRC fault occurs in different phase/phases. The angle difference mentioned above is defined as the “fault localization indicator,” $\chi$, which is expressed as follows:

$$\chi = \gamma/2 - \theta_{P_1}.$$  
(15)

![Fig. 6. MFPO angular position waveforms. (a) Healthy condition. (b) HRC SP faults. (c) HRC TPN faults. (d) HRC TPA faults.](image)

The results of the fault localization indicator $\chi$ are listed in Table II. As can be seen, for each type of HRC faults, an approximate 72° difference in sequence is observed, e.g., the fault localization indicator $\chi$ of the HRC fault in
phase-A is leading that in phase-B by about 72°, i.e., \(-21.3°\)–\((-93.5°) = 72.2° \approx 72°\). In order to facilitate the localization of faulty phase/phases, the faulty phase localization regions are set according to the results in Table II, as shown in Fig. 7.

**TABLE II** Simulated Results of Fault Localization Indicator

<table>
<thead>
<tr>
<th>SP faults</th>
<th>(\chi)</th>
<th>TPN faults</th>
<th>(\chi)</th>
<th>TPA faults</th>
<th>(\chi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-A</td>
<td>-2 1.3°</td>
<td>Phase-A&amp;C</td>
<td>-4.3°</td>
<td>Phase-A&amp;B</td>
<td>-62.3°</td>
</tr>
<tr>
<td>Phase-B</td>
<td>-93.5°</td>
<td>Phase-B&amp;D</td>
<td>-76.2°</td>
<td>Phase-B&amp;C</td>
<td>-134.2°</td>
</tr>
<tr>
<td>Phase-C</td>
<td>-165.4°</td>
<td>Phase-C&amp;E</td>
<td>-14.8.3°</td>
<td>Phase-C&amp;D</td>
<td>-205.4°</td>
</tr>
<tr>
<td>Phase-O</td>
<td>-237.2°</td>
<td>Phase-D&amp;A</td>
<td>-220.6°</td>
<td>Phase-D&amp;E</td>
<td>-277.9°</td>
</tr>
<tr>
<td>Phase-E</td>
<td>-309.5°</td>
<td>Phase-E&amp;B</td>
<td>-292.8°</td>
<td>Phase-E&amp;A</td>
<td>-350.3°</td>
</tr>
</tbody>
</table>

Based on the results in Fig. 7, the faulty phase/phases can be successfully localized, e.g., for SP faults, if the fault localization indicator \(\chi\) is located in the red region in Fig. 7(a), the faulty phase-A can be identified, whereas if it is located in the yellow region, the faulty phase-B can be identified. The same rule can be used for other cases as well as for the cases of the other two fault types, i.e., TPN faults and TPA faults in Fig. 7(b) and (c), respectively.

**D. Estimation of HRC Fault Severity**

Different HRC fault severities would have different effects on the motor-drive system, which is expected to result in different symmetrical components as well as different MFPO phenomena.

For SP faults (taking phase-A HRC fault as an example), the results of the detection indicator \(\xi\) with different additional resistances \(R_{\text{add}}\) are shown in Fig. 8. As can be seen, the detection indicator \(\xi\) increases in a monotonically unambiguous manner as the additional resistance \(R_{\text{add}}\) increases. Hence, the detection indicator \(\xi\) can be expressed as a function of the additional resistance as follows:

\[
\xi = f(R_{\text{add}}).
\]
Then, the additional resistance can be estimated by the inverse function of (16), which can be expressed as

$$\xi = f(R_{\text{add}}).$$

(17)

For TPN faults and TPA faults, taking phase-A&C fault as an example, the results of the detection indicator $\xi$ and the localization indicator $\chi$ with variation of additional resistance in phase-A and in phase-C, $R_{\text{add},A}$ and $R_{\text{add},C}$, are shown in Fig. 9. Based on the results in Fig. 9, response surface models can be developed with the response surface methodology [34], [35], which can be expressed as

\[
\begin{align*}
\xi &= f(R_{\text{add},A}, R_{\text{add},C}) \\
\chi &= f(R_{\text{add},A}, R_{\text{add},C}).
\end{align*}
\]

(18)
Fig. 9. Variation of the detection indicator and localization indicator with different $R_{\text{add,A}}$ and $R_{\text{add,C}}$. (a) Detection indicator $\xi$. (b) Localization indicator $\chi$.

The curve fitting technique is used to calculate the regression coefficients associated with each second-order response surface, which can be expressed as

\[
\begin{align*}
\xi &= m_{20} \cdot (R_{\text{add,A}})^2 + m_{02} \cdot (R_{\text{add,C}})^2 + m_{11} \cdot R_{\text{add,A}} \cdot R_{\text{add,C}} \\
&\quad + m_{10} \cdot R_{\text{add,A}} + m_{01} \cdot R_{\text{add,C}} + m_{00} \\
\chi &= n_{20} \cdot (R_{\text{add,A}})^2 + n_{02} \cdot (R_{\text{add,C}})^2 + n_{11} \cdot R_{\text{add,A}} \cdot R_{\text{add,C}} \\
&\quad + n_{10} \cdot R_{\text{add,A}} + n_{01} \cdot R_{\text{add,C}} + n_{00}
\end{align*}
\]

(19)

Hence, the additional resistances $R_{\text{add,A}}$ and $R_{\text{add,C}}$ can be estimated by solving (19) based on an inverse model, which can be expressed as

\[
\begin{align*}
R_{\text{add,A}} &= f^{-1}(\xi, \chi) \\
R_{\text{add,C}} &= f^{-1}(\xi, \chi)
\end{align*}
\]

(20)

The same rule can be applied to the other scenarios in TPN faults, e.g., phase-B&D fault, as well as in TPA faults, e.g., phase-A&B fault. From these results, it is interesting to note that in phase-A&C fault as shown in the red region of Fig. 7(b), when the two additional resistances $R_{\text{add,A}}$ and $R_{\text{add,C}}$ are equal, the fault localization indicator $\chi$ is aligning with the central axis of the red region. By contrast, the fault localization indicator $\chi$ is
located in the top half part of the red region when $R_{\text{add},C} > R_{\text{add},A}$, whereas it is located in the bottom half part of the red region when $R_{\text{add},A} > R_{\text{add},C}$, as marked in Fig. 7(b). Similar relations are also marked for other scenarios in Fig. 7(b) and (c), respectively.

SECTION IV. Experimental Validation

In order to verify the theoretical analysis and simulation results, a complete motor-drive system has been built and some experimental tests have been carried out. The experimental setup mainly consists of a five-phase PMSM prototype, sensors, a five-phase gate drive, and a field-programmable gate array (FPGA) based controller, as shown in Fig. 10. The five-phase PMSM prototype is a dual-rotor surface-mounted PMSM. More details about the five-phase PMSM could be found in Table I. The sensors include LEM current sensors and a speed sensor, which are used for measuring the five-phase current signals and the position/speed signal of the rotor, respectively. The FPGA-based controller is a commercially available FPGA (Altera-Cyclone III EP3C25Q240, 50 MHz, 24624 Logic Elements, 508 KB RAM) with embedded processors, which is used as the microcontroller for vector control purpose, data acquisition, and signal processing.

Fig. 10. Experimental setup. (a) Test platform with the PMSM prototype. (b) Five-phase drive. (c) HRC fault implementation.

The phase current waveforms under healthy condition and with an HRC fault in phase-A ($R_{\text{add}} = 0.8$ Ω) are shown in Fig. 11. The current symmetrical components are shown in Fig. 12. As can be seen, under healthy condition, the five-phase currents are symmetrical as shown in Fig. 11(a), and only the positive sequence 1 component is nonzero in the symmetrical components domain as shown in Fig. 12(a). By contrast, under faulty condition, the symmetry of the phase currents is disturbed, and the phase-A current is smaller than other phase currents [see Fig. 11(b)]. In addition, besides the positive sequence 1 component, there are nonzero positive sequence 2, negative sequence 1, and negative sequence 2 components [see Fig. 12(b)], which are different from that under healthy condition.
Fig. 11. Phase current waveform. (a) Healthy condition. (b) HRC fault in phase-A.
The real-time experimental results under the rated operating point of 18 N-m at 100 r/min are shown in Fig. 13. The setting for the ten stages during the whole detection process and the average value of the estimated additional resistance from Fig. 13(d) are listed in Table III.

Fig. 12. Current symmetrical components waveform. (a) Healthy condition. (b) HRC fault in phase-A.
As can be seen, in stage ① from 0 to 27.27 ms, under healthy condition, the detection indicator $\xi$ is smaller than the preset threshold, whereas after that from 27.27 ms to the end, the detection indicator $\xi$ is larger than the threshold for all different fault scenarios. These results indicate that the HRC fault can be successfully detected and alarmed relative to healthy condition. It should be noted that the threshold is preset as 0.1, which is selected as 2.5 times of the maximum value of the measured detection indicator $\xi$ under healthy condition, i.e., 0.04. On the other hand, it is smaller than the minimum value of the detection indicator $\xi$ under faulty condition.
conditions in stages ②–⑩ from 27.27 to 272.73 ms, i.e., 0.17. Hence, the preset threshold is good to avoid false alarms.

In stages ②–④ from 27.27 to 109.09 ms, under SP fault condition with $R_{\text{add,A}}$ = 0.4 Ω, 0.8 Ω, and 1.6 Ω, respectively, the fault type indicator $\lambda$ is kept approximately equal to one, i.e., $\lambda = 1$. Thus, the SP fault type can be distinguished. In addition, the fault localization indicator $\chi$ is maintained within the range of −57°~15°, i.e., the red region in Fig. 7(a). Thus, the faulty phase of phase-A can be localized. Moreover, based on the relationship between the detection indicator and the additional resistance from (17), the fault severity can be accurately estimated, as shown in Fig. 13(d) and listed in Table III. More specifically, the average values of the estimated additional resistance of $R_{\text{add,A}}$ from experimental results are 0.41, 0.79, and 1.62 Ω for stages ②, ③, and ④, respectively. These estimated additional resistances are in good agreement with the setting values in the detection process, which are 0.4, 0.8, and 1.6 Ω, respectively, as shown in Table III.

In stages ⑤–⑦ from 109.09 to 190.91 ms, under TPN fault conditions, the fault type indicator $\lambda$ is kept larger than one, i.e., $\lambda > 1$, whereas the fault localization indicator $\chi$ is maintained within the range of −40°~32°, i.e., the red region in Fig. 7(b). In addition, based on the inverse rms model from (20), the average values of the estimated additional resistance are also in good agreement with their corresponding setting values included in Table III. It should be noted that slight pulsation can be observed in the estimated resistance results in Fig. 13(d) during these stages. This may be due to the fact that HRC faults inevitably lead to mechanical vibration and measurement difficulties.

Similarly, in stages ⑧–⑩ from 190.91 to 272.73 ms, under TPA fault conditions, the fault type indicator $\lambda$ is kept smaller than one, i.e., $\lambda < 1$, whereas the fault localization indicator $\chi$ is maintained within the range of −98°~−26°, i.e., the red region in Fig. 9(c). In addition, the fault severity is also well estimated, refer to Table III. The discrepancies in stages ⑧ and ⑨ are relatively large, which may be due to the fault masking difficulties associated with the compensation action of the closed-loop vector-controlled drive. In addition, the inherent asymmetry in the motor-drive prototype due to the imperfections of manufacturing and assembling process for the five-phase PMSM prototype, material properties variations, as well as measurement inaccuracies, can also contribute to the discrepancy.

Overall, it is fair to state that the estimated resistance and the setting resistances are in acceptable agreement from the results listed in Table III. These experimental results verified the accuracy of the previous theoretical analysis as well as the effectiveness of the presented HRC diagnostic approach.

SECTION V. Conclusion
This article presented an online diagnostic approach of HRC fault in five-phase PMSMs. It was found that a “swing-like” MFPO phenomenon can be observed under HRC fault condition compared to the healthy condition. Moreover, the symmetrical component of the positive sequence 1 phasor vector would not be affected by any oscillations caused by an HRC fault, due to the compensation action of the closed-loop vector-controlled drive. Based on the MFPO phenomenon and the symmetrical components method, the HRC fault was successfully detected. Different HRC fault types, i.e., 1) SP faults, e.g., HRC fault in phase-A, 2) TPN faults, e.g., HRC fault in phase-A&C, and 3) TPA faults, e.g., HRC fault in phase-A&B, were distinguished. Furthermore, the faulty phase/phases were also localized, and the HRC fault severity was accurately estimated. It should be noted that even though the results presented in this article are specific for the investigated PMSM, this presented diagnostic approach can be extended/applied to other PMSMs.

The presented diagnostic approach has the following advantages over existing methods.
1. Noninvasive: There are no additional signals injected into the motor-drive system in this approach. The diagnostic process has no impact on the operation smoothness of the motor-drive system.

2. Low implementation cost: This approach requires no additional sensors or hardware except the current sensors that are typically already available in the closed-loop vector-controlled drive.

3. Online diagnosis with closed-loop vector-controlled drives: The unaffected symmetrical component of the positive sequence 1 is utilized as a reference/benchmark. Hence, the difficulties associated with the compensation action of the closed-loop vector-controlled drive are overcome. Moreover, downtime is avoided with this online diagnostic approach.

4. Fast detection speed: The required current signals within only one electrical cycle are needed to recognize an HRC fault.

The main limitation of the HRC diagnostic approach is that the diagnosis process is implemented under steady-state operating condition. This limitation could be overcome by confirming the steady-state operating condition first, before the diagnostic approach is applied.

In conclusion, the presented diagnostic approach enables one to detect HRC fault at an incipient stage to prevent further cascaded damage to the machine and the involved system.

References


