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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 on-line approach for diagnosing high-resistance connection (HRC) faults in five-phase permanent magnet synchronous motor (PMSM) drives is presented in this paper. The development of this approach is based on a so-called “magnetic field pendulous oscillation (MFPO)” technique and symmetrical components method. Under HRC faulty 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 discriminated. These fault types include (i) single-phase faults, e.g., HRC fault in phase-A, (ii) two-phase non-adjacent faults, e.g., HRC fault in phase-A&C, and (iii) 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 typically are 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.

Index Terms—Fault diagnosis, high-resistance connection, magnetic field pendulous oscillation, permanent magnet motor, symmetrical components.

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, multi-phase (>3) PMSM drive systems exhibit lower torque ripple, reduced power per phase, and improved fault-tolerance capability [3].

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However, multi-phase 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 multi-phase 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 can not 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 paper.

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, while 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 off-line method is that it can only be implemented when the machine is at standstill. Building upon the work in [8], an improved strategy for on-line HRC fault diagnosis is presented in [9], in which a DC signal instead of high-frequency AC signal is injected into the d -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 non-invasive 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 α_3 - β_3 and α_5 - β_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 on-line 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 are 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 (EMF) 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, are necessary in these ZSVC-based methods as shown in [15]-[18], which may not be available in most industrial applications.

Differing from the previous works, this paper brings new contributions by presenting an on-line 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 healthy condition. Then, various HRC fault types are identified and discriminated. These fault types include (i) single-phase faults, *e.g.*, HRC fault in phase-A, (ii) two-phase non-adjacent faults, *e.g.*, HRC fault in phase-A&C, and (iii) two-phase adjacent 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 four phase currents is needed for the five-phase PMSM drive system, while these currents typically have been 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 paper is organised 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, conclusions are drawn in Section V.

II. MFPO PHENOMENON DUE TO HRC FAULT

The investigated five-phase PMSM drive system is schematically depicted in Fig. 1, while 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. It should be noted that the HRC fault is modelled by adding an additional resistance, R_{add} , which is in series connection with a phase winding.

A. MFPO Phenomenon

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

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

where $V_{a,b,c,d,e}$, $R_{a,b,c,d,e}$, $i_{a,b,c,d,e}$, and $\psi_{a,b,c,d,e}$ are the phase voltages, resistances, currents, and flux linkages, respectively.

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:

$$i_{a,b,c,d,e} = \sqrt{2} \cdot I_m \cdot \cos[\omega_s t - (h-1)2\pi/5] \quad (2)$$

where I_m is the root-mean-square value of phase currents, ω_s is the synchronous speed in rad/s, h takes 1, 2, 3, 4, and 5 corresponding to the phase sequent for i_a , i_b , i_c , i_d , and i_e , respectively. According to eq. (2), the current space-vector, $\vec{I}_s$, can be expressed as:

$$\vec{I}_s(t) = 2/5 \cdot [i_a(t) + \alpha \cdot i_b(t) + \alpha^2 \cdot i_c(t) + \alpha^3 \cdot i_d(t) + \alpha^4 \cdot i_e(t)] \quad (3)$$

$$= I_m \cdot e^{j\omega_s t}$$

where α is the phase-shift coefficient, $\alpha = \exp(j2\pi/5)$. Hence, the motor is controlled in such a way that $\vec{I}_s$ is the only non-null 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, $\vec{V}_s$, and flux linkage space-vector, $\vec{\psi}_s$. The electromagnetic torque of the PMSM can be expressed as follows:

$$T_e = 5/2 \cdot P \cdot (\vec{\psi}_s \times \vec{I}_s) \quad (4)$$

where P is the number of rotor pole pairs.

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 paper, the faulty phase current, i_a , would be distorted. The phase currents in eq. (2) are re-presented as follows:

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

TABLE I
SPECIFIC PARAMETERS OF THE INVESTIGATED PMSM

Parameter	Value	Parameter	Value
Number of stator slots	40	PM flux linkage (Wb)	0.037
Number of rotor poles	44	<i>d</i> -axis inductance (mH)	0.85
Rated speed (r/min)	100	<i>q</i> -axis inductance (mH)	0.87
Rated torque (Nm)	18	Phase resistance (ohm)	0.67

$$\left. \begin{aligned} i_a &= \sqrt{2} \cdot I_m \cdot \cos(\omega_s t + \varphi_a) \\ i_b &= \sqrt{2} \cdot I_m \cdot \cos(\omega_s t - 2\pi/5); \quad i_c = \sqrt{2} \cdot I_m \cdot \cos(\omega_s t - 4\pi/5) \\ i_d &= \sqrt{2} \cdot I_m \cdot \cos(\omega_s t - 6\pi/5); \quad i_e = \sqrt{2} \cdot I_m \cdot \cos(\omega_s t - 8\pi/5) \end{aligned} \right\} (5)$$

where I_m' is the reduced current magnitude and φ_a' is the phase angle of faulted phase-A current. 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, $\bar{I}_s'$, can be re-written as linear combinations of a forward vector, $\bar{I}_f'$, which rotates CCW at synchronous speed, ω_s , and a backward vector, $\bar{I}_b'$, which rotates also at synchronous speed but in clockwise (CW) direction, $-\omega_s$, as expressed as follows:

$$\vec{I}'_s = \vec{I}'_f \cdot e^{j\omega_s t} + \vec{I}'_b \cdot e^{-j\omega_s t} = (\vec{I}'_f + \vec{I}'_b \cdot e^{-j2\omega_s t}) \cdot e^{j\omega_s t} = \vec{I}'_f + \vec{I}'_b \quad (6)$$

Referring to eq. (4), the resultant current space-vector, $\bar{I}_s'$, 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, $\bar{I}_f'$, and reduce the magnitude of the backward current space-vector, $\bar{I}_b'$. As a result, the voltage space-vector, $\bar{V}_s$, and the resultant flux-linkage space-vector, $\bar{\psi}_s$, would also consist of a forward component, $\bar{V}_f'$ and $\bar{\psi}_f'$, and a backward component, $\bar{V}_b'$ and $\bar{\psi}_b'$, as expressed as follows [19], [20]:

$$\vec{V}_s' = \vec{V}_f' + \vec{V}_b' = V_f' \cdot e^{j\omega_s t} + V_b' \cdot e^{-j\omega_s t} = (V_f' + V_b' \cdot e^{-j2\omega_s t}) \cdot e^{j\omega_s t} \quad (7)$$

$$\vec{\psi}'_s = \vec{\psi}'_f + \vec{\psi}'_b = \psi'_f \cdot e^{j\omega_s t} + \psi'_b \cdot e^{-j\omega_s t} = (\psi'_f + \psi'_b \cdot e^{-j2\omega_s t}) \cdot e^{j\omega_s t} \quad (8)$$

The aforementioned compensation action cannot fully cancel the backward current space-vector in eq. (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 eq. (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

Fig. 2 Loci of space-vectors of the PMSM drive system under HRC fault condition.

exist for all the electrical quantity space-vectors, which rotates CCW at synchronous speed, ω_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, while 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 “Magnetic Field Pendulous Oscillation (MFPO)” phenomenon.

The original concept of the MFPO is introduced in [21], [22] and this phenomenon has been previously used to detect the interturn fault in [23] and broken rotor bar fault in [24] for three-phase induction motors, as well as open-phase fault in [25] 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 [21]-[24]. In this way, at least four voltage sensors and four current sensors are needed for the five-phase PMSM drive system investigated in this paper. By contrast, a phase-locked loop (PLL) technique is used in [25] 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 re-developed and improved by combining with the symmetrical components method. As a result, only sensing four phase currents is needed to implement the HRC fault diagnostic approach, while these currents typically have been 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 [26]. It has been attempted to be used in the diagnosis of interturn faults, but mainly focused on three-phase induction motors [27], [28]. 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→B→C→D→E, see Fig. 3(a)], positive sequence 2 [A→C→E→B→D, see Fig. 3(b)], negative sequence 1 [A→E→D→C→B, see Fig. 3(c)], negative sequence 2 [A→D→B→E→C, see Fig. 3(d)], and zero sequence [see Fig. 3(e)] [29]. The five sequence components can be calculated as follows:

$$\begin{bmatrix} \dot{i}_{p1} \\ \dot{i}_{p2} \\ \dot{i}_{n1} \\ \dot{i}_{n2} \\ \dot{i}_0 \end{bmatrix} = \frac{1}{5} \begin{bmatrix} 1 & \alpha & \alpha^2 & \alpha^3 & \alpha^4 \\ 1 & \alpha^3 & \alpha & \alpha^4 & \alpha^2 \\ 1 & \alpha^4 & \alpha^3 & \alpha^2 & \alpha \\ 1 & \alpha^2 & \alpha^4 & \alpha & \alpha^3 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \dot{i}_a \\ \dot{i}_b \\ \dot{i}_c \\ \dot{i}_d \\ \dot{i}_e \end{bmatrix} \quad (9)$$

where $\dot{i}_{p1}$, $\dot{i}_{p2}$, $\dot{i}_{n1}$, $\dot{i}_{n2}$, and $\dot{i}_0$ are the phasor vectors of positive sequence 1, positive sequence 2, negative sequence 1, negative sequence 2, and zero sequence, respectively. $\dot{i}_a$, $\dot{i}_b$, $\dot{i}_c$, $\dot{i}_d$, and $\dot{i}_e$ are the phasor vectors of the five phase currents. For example, the positive sequence 1 phasor vector, $\dot{i}_{p1}$, is calculated as follows:

$$\begin{aligned} \dot{i}_{p1} &= 1/5 \cdot (\dot{i}_a + \alpha \cdot \dot{i}_b + \alpha^2 \cdot \dot{i}_c + \alpha^3 \cdot \dot{i}_d + \alpha^4 \cdot \dot{i}_e) \\ &= 1/5 \cdot (I_a \angle \varphi_a + \alpha \cdot I_b \angle \varphi_b + \alpha^2 \cdot I_c \angle \varphi_c + \alpha^3 \cdot I_d \angle \varphi_d + \alpha^4 \cdot I_e \angle \varphi_e) \quad (10) \\ &= I_{p1} \angle \theta_{p1} \end{aligned}$$

where I_a , I_b , I_c , I_d , and I_e are the magnitude of $\dot{i}_a$, $\dot{i}_b$, $\dot{i}_c$, $\dot{i}_d$, and $\dot{i}_e$, respectively, while φ_a , φ_b , φ_c , φ_d , and φ_e are the corresponding phase angle. I_{p1} and θ_{p1} are the magnitude and phase angle of the positive sequence 1 phasor vector, $\dot{i}_{p1}$. 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, θ_{p2} , θ_{n1} , and θ_{n2} , can also be calculated by eq. (9). The difference between the calculations of the positive sequence 1 phasor vector, $\dot{i}_{p1}$, in eq. (10) and the current space-vector, $\vec{I}_s$, in eq. (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 paper, 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, $\dot{i}_{p1}$, 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, $\dot{i}_{p1}$, will always coincide/overlap with the axis of the forward current space-vector, $\vec{I}_f$, in the space-vector diagram (see Fig. 2). Accordingly, the positive sequence 1 phasor vector, $\dot{i}_{p1}$, 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

Fig. 3 Symmetrical components for five-phase systems. (a) Positive sequence 1. (b) Positive sequence 2. (c) Negative sequence 1. (d) Negative sequence 2. (e) Zero sequence.

Fig. 4 Positive sequence 1 current profiles under both healthy and HRC fault conditions.

sequence 1 phasor vector, $\dot{i}_{p1}$, as shown in Fig. 2, which can be expressed as follows:

$$\delta(t) = \angle \vec{I}_s(t) - \theta_{p1}(t) \quad (11)$$

where $\angle \vec{I}_s(t)$ is the phase angle of the current space-vector.

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 healthy condition;
- 2) Discrimination of different HRC fault types. As mentioned in [14], [30], the most common HRC fault occurs in only one phase. Even so, the fault in two phases is also taken into account for completeness of this paper. As a result, three different HRC fault types are investigated in this paper. These fault types include (i) single-phase (SP) faults, e.g., HRC fault in phase-A, (ii) two-phase non-adjacent (TPN) faults, e.g., HRC fault in phase-A&C, and (iii) two-phase adjacent (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 eq. (9), while 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 non-zero constant value under steady-state operating condition after an HRC fault. Hence, a detection indicator, ξ , is defined as the ratio of the sum of I_{P2} and I_{N2} to I_{P1} , which is expressed as follows:

$$\xi = (I_{P2} + I_{N2}) / I_{P1} \quad (12)$$

It should be noted that I_{N1} is not included since the the negative sequence 1 phasor vector is a non-significant component in HRC faults. Accordingly, during the detection process, an HRC fault can be alarmed when the detection indicator, ξ , is larger than a pre-set threshold.

B. Discrimination 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:

$$\lambda = I_{P2} / I_{N2} \quad (13)$$

The results of the fault type indicator, λ , are shown in Fig. 5. The fault cases with $R_{add}=0.4$ ohm, 0.8 ohm (approximately equal to the rated resistance), and 1.6 ohm, are included. As can be seen, for all the fault scenarios in SP faults, the fault type indicator, λ , is always approximately equal to one, *i.e.*, $\lambda \approx 1$; For TPN faults, the fault type indicator, λ , is larger than one, *i.e.*, $\lambda > 1$; For TPA faults, the fault type indicator, λ , is smaller than one, *i.e.*, $\lambda < 1$. Hence, the fault type indicator, λ , provides good information for discriminating the HRC fault types.

C. Localization of Faulty Phase/Phases

Under faulty condition, the phase angle of the positive sequence 1 phasor vector, θ_{P1} , is not affected by any oscillation caused by the HRC fault, while the the current space-vector, $\bar{I}_s$, are resolved into two components, *i.e.*, the forward component, $\bar{I}_f$, and the backward component, $\bar{I}_b$. Both the two components rotate at synchronous speed, ω_s , but in opposite direction to each other. In other words, the backward component, $\bar{I}_b$, is rotating $-2\omega_s$ with respect to the forward component, $\bar{I}_f$, see eq. (6). Hence, under faulty condition, the MFPO angular position, $\delta(t)$, in eq. (11), would be oscillating with a frequency equal to twice the synchronous frequency, which can be re-written as follows:

$$\delta(t) = \Delta\delta_s \cdot \cos(2\omega_s \cdot t) \quad (14)$$

where $\Delta\delta_s$ is the range/magnitude of the MFPO angular position, which is named as the “swing angle”.

The simulated MFPO angular position waveforms under HRC fault conditions ($R_{add}=0.8$ ohm) are shown in Fig. 6. It is interesting to note that there are two periods in these MFPO angular position waveforms in one electrical cycle, which confirms the second-harmonic nature of the MFPO phenomenon as previously shown in eq. (14). Moreover, for each type of the HRC faults, *e.g.*, SP faults in Fig. 6(a), there is a 72-degree phase-shift between two adjacent faults of the five

Fig. 5 Fault type indicator results for the three different HRC fault types.

Fig. 6 MFPO angular position waveforms. (a) HRC SP faults. (b) HRC TPN faults. (c) HRC TPA faults.

fault scenarios. More specifically, the MFPO angular position waveform of the HRC fault in phase-A is 72-degree leading compared to that of the HRC fault in phase-B, while the MFPO angular position waveform of the HRC fault in phase-B is 72-degree 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, i_{P1} , would not be affected by any oscillation 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 at the first instant of time when the sampling is started, $\theta_{p1}(1)$, will be constant for each fault case, while it will be significantly different (72-degree 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”, χ , which is expressed as follows:

$$\chi = \gamma/2 - \theta_{p1}(1) \quad (15)$$

The results of the fault localization indicator, χ , are listed in Table II. As can be seen, for each type of HRC faults, an approximate 72-degree difference in sequence is observed, e.g., the fault localization indicator, χ , of the HRC fault in phase-A is leading that in phase-B by about 72 degrees, i.e., $-21.3^\circ - (-93.5^\circ) = 72.2^\circ \approx 72^\circ$. 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. 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, χ , is located in the red region in Fig. 7(a), the faulty phase-A can be identified, while 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, ξ , with different additional resistances, R_{add} , are shown in Fig. 8. As can be seen, the detection indicator, ξ , increases in a monotonically unambiguous manner as the additional resistance, R_{add} , increases. Hence, the detection indicator, ξ , can be expressed as a function of the additional resistance as follows:

$$\xi = f(R_{add}) \quad (16)$$

Then, the additional resistance can be estimated by the inverse function of eq. (16), which can be expressed as:

$$R_{add} = f^{-1}(\xi) \quad (17)$$

For TPN faults and TPA faults, taking phase-A&C fault as an example, the results of the detection indicator, ξ , and the localization indicator, χ , with variation of additional resistance in phase-A and in phase-C, R_{add_A} and R_{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 (RSM) [31], [32], which can be expressed as:

$$\begin{cases} \xi = f(R_{add_A}, R_{add_C}) \\ \chi = f(R_{add_A}, R_{add_C}) \end{cases} \quad (18)$$

Hence, the additional resistances, R_{add_A} and R_{add_C} , can be estimated based on an inverse model as expressed as:

$$\begin{cases} R_{add_A} = f^{-1}(\xi, \chi) \\ R_{add_C} = f^{-1}(\xi, \chi) \end{cases} \quad (19)$$

TABLE II
SIMULATED RESULTS OF FAULT LOCALIZATION INDICATOR

SP faults	χ	TPN faults	χ	TPA faults	χ
Phase-A	-21.3°	Phase-A&C	-4.3°	Phase-A&B	-62.3°
Phase-B	-93.5°	Phase-B&D	-76.2°	Phase-B&C	-134.2°
Phase-C	-165.4°	Phase-C&E	-148.3°	Phase-C&D	-205.4°
Phase-D	-237.2°	Phase-D&A	-220.6°	Phase-D&E	-277.9°
Phase-E	-309.5°	Phase-E&B	-292.8°	Phase-E&A	-350.3°

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_{add_A} and R_{add_C} , are equal, the fault localization indicator, χ , is aligning with the central axis of the red region. By contrast, the fault localization indicator, χ , is located in the top half part of the red region when $R_{add_C} > R_{add_A}$, while it is located in the bottom half part of the red region when $R_{add_A} > R_{add_C}$, as marked in Fig. 7(b). Similar relations are also marked for other scenarios in Fig. 7(b) and (c), respectively.

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 an FPGA-based controller, a five-phase gate drive, current sensors, and a five-phase dual-rotor surface-mounted PMSM prototype, as shown in Fig. 10.

The real-time experimental results are shown in Fig. 11. The setting for the 10 stages during the whole detection process, and the average value of the estimated additional resistance from Fig. 11(d), are listed in Table III.

As can be seen, in stage ① from 0~27.27ms, under healthy condition, the detection indicator, ξ , is smaller than the pre-set threshold, while after that from 27.27ms to the end, the detection indicator, ξ , 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.

In stage ②-④ from 27.27~109.09ms, under SP fault condition with $R_{add_A} = 0.8$ ohm, 1.6 ohm, and 2.4 ohm, respectively, the fault type indicator, λ , is kept approximately equal to one, i.e., $\lambda \approx 1$. Thus, the SP fault type can be discriminated. In addition, the fault localization indicator, χ , is maintained within the range of $-57^\circ \sim 15^\circ$, 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 eq. (17), the fault severity can be accurately estimated, as shown in Fig. 11(d) and listed in Table III. More specifically, the average values of the estimated additional resistance of R_{add_A} from experimental results are 0.79 ohm, 1.62 ohm, and 2.38 ohm for the stage ②, ③, and ④, respectively. These estimated additional resistances are in good agreement with the setting values in the detection process, which are 0.8 ohm, 1.6 ohm, and 2.4 ohm, respectively, as shown in Table III.

In stage ⑤-⑦ from 109.09~190.91ms, under TPN fault conditions, the fault type indicator, λ , is kept larger than one,

Fig. 7 Fault localization indicator results. (a) SP faults. (b) TPN faults. (c) TPA faults.

Fig. 8 HRC fault severity estimation for SP faults.

Fig. 9 Variation of the detection indicator and localization indicator with different R_{add_A} and R_{add_C} . (a) Detection indicator, ξ . (b) Localization indicator, χ .

i.e., $\lambda > 1$, while the fault localization indicator, χ , is maintained within the range of $-40^\circ \sim 32^\circ$, *i.e.*, the red region in Fig. 7(b). In addition, based on the inverse RMS model from eq. (19), 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. 11(d) during these stages. This may be due to the fact that HRC faults inevitably lead to mechanical vibration and measurement

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

difficulties.

Similarly, in stage ⑧–⑩ from 190.91~272.73ms, under TPA fault conditions, the fault type indicator, λ , is kept smaller than one, *i.e.*, $\lambda < 1$, while the fault localization indicator, χ , is maintained within the range of $-98^\circ \sim 26^\circ$, *i.e.*, the red region in Fig. 9(c). In addition, the fault severity is also accurately estimated, refer to Table III.

These experimental results verified the accuracy of the previous theoretical analysis as well as the effectiveness of the presented HRC diagnostic approach.

V. CONCLUSION

This paper presented an on-line 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 oscillation 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 is successfully detected. Different HRC fault types, *i.e.*, (i) SP faults, *e.g.*, HRC fault in phase-A, (ii) TPN faults, *e.g.*, HRC fault in phase-A&C, and (iii) TPA faults, *e.g.*, HRC fault in

Fig. 11 Real-time experimental results. (a) Detection indicator. (b) Fault type indicator. (c) Localization indicator. (d) Estimated resistance.

Stage	Time (ms)	Setting R_{add} (ohm)	Estimated R_{add} (ohm)
①	0~27.27	-	-
②	27.27~54.55	$R_{add_A}=0.8$	$R_{add_A}=0.79$
③	54.55~81.82	$R_{add_A}=1.6$	$R_{add_A}=1.62$
④	81.82~109.09	$R_{add_A}=2.4$	$R_{add_A}=2.38$
⑤	109.09~136.36	$R_{add_A}=0.8$ $R_{add_C}=0.8$	$R_{add_A}=0.81$ $R_{add_C}=0.76$
⑥	136.36~163.64	$R_{add_A}=0.8$ $R_{add_C}=1.6$	$R_{add_A}=0.85$ $R_{add_C}=1.56$
⑦	163.64~190.91	$R_{add_A}=1.6$ $R_{add_C}=0.8$	$R_{add_A}=1.69$ $R_{add_C}=0.79$
⑧	190.91~218.18	$R_{add_A}=0.8$ $R_{add_B}=0.8$	$R_{add_A}=0.68$ $R_{add_B}=0.67$
⑨	218.18~245.45	$R_{add_A}=0.8$ $R_{add_B}=1.6$	$R_{add_A}=0.91$ $R_{add_B}=1.82$
⑩	245.45~272.73	$R_{add_A}=1.6$ $R_{add_B}=0.8$	$R_{add_A}=1.71$ $R_{add_B}=0.84$

phase-A&B, are discriminated. Furthermore, the faulty phase/phases are also localized, and the HRC fault severity is accurately estimated.

The presented diagnostic approach has the following

advantages over the existing methods:

- 1) Non-invasive: There is 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 which typically are already available in the closed-loop vector-controlled drive.
- 3) On-line 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 is overcome. Moreover, downtime is avoided with this on-line diagnostic approach.
- 4) Fast detection speed: The required current signals within only one electrical cycle are needed to recognize an HRC fault.

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.

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