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Diagnosis of Open-Phase Faults for a Five-Phase PMSM Fed by a Closed-Loop Vector-Controlled Drive Based on Magnetic Field Pendulous Oscillation Technique

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Abstract—An on-line diagnostic approach of open-phase faults for a five-phase permanent magnet synchronous motor (PMSM) fed by a closed-loop vector-controlled drive is presented in this paper. This approach is accomplished based on the magnetic field pendulous oscillation (MFPO) phenomenon, in which a significant “swing-like” pendulous oscillation in the magnetic field is observed in case of open-phase faults. According to analysis of the signatures of MFPO patterns under faulty conditions, all possible open-phase faults are detected, including single-phase open faults, two-adjacent phase open faults, and two-nonadjacent phase open faults. Moreover, this approach is capable of localizing the faulted phase/phases by further extracting the phase angle features of MFPO angular position waveforms under faulty conditions. Meanwhile, in order to minimize the number of sensors to reduce the implementation cost of this diagnostic approach, a phase-locked loop (PLL) technique is developed to overcome the fault masking difficulties associated with the compensation action of the closed-loop vector-controlled drive. As a result, this diagnostic approach only requires four current sensors, which are typically already available in five-phase PMSM drive systems for control purpose. Finally, experimental results demonstrate the effectiveness of the presented approach.

Index Terms—Fault diagnosis, magnetic field pendulous oscillation (MFPO), open-phase fault, permanent magnet synchronous motor (PMSM).

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I. INTRODUCTION

THE RELIABILITY of motor-drive systems is of significant importance in safety-critical applications, *e.g.*, aircraft, ship propulsion, and electric vehicles. Compared to the conventional three-phase permanent magnet synchronous motor (PMSM) drive systems, five-phase counterparts have exhibited the advantages of high torque density and improved fault-tolerance capability [1], [2]. Hence, a five-phase PMSM drive system is investigated in this paper.

Five-phase PMSMs are not immune to all electrical faults. Due to the destructive nature and potential propagation of the faults, it is essential to diagnose these faults in an incipient stage. Consequently, further damage to the motor-drive system could be prevented, and preferably a remedial fault-tolerance control strategy could be triggered to maintain the system functionality as much as possible [3], [4]. Among all the electrical faults in PMSM drive systems, the open-phase fault is one of the most common faults, which could be caused by electrical failures of inverter phase legs, external cable connection failures, or internal stator winding ruptures [5].

In recent years, the development of open-phase fault diagnosis for electric machines has received considerable attention. In [6], Gajanayake *et al.* diagnosed open-phase faults by calculating the root-mean-square (RMS) value of phase currents. This method is straightforward, while it has a relatively slow fault detection speed (usually requires more than 3 electrical cycles), and imposes a heavy computational burden (CPU resource and memory-consuming), as well as facing the possibility of false alarms. In [7], Kuruppu *et al.* presented a single-phase open fault diagnostic method for a three-phase PMSM based on the *d-q* current signatures. By comparing the phase shift in the fault diagnosis signal with respect to the actual electrical angle, this method is capable of identifying the faulted phase. Compared to the aforementioned phase current RMS value calculation method, this method exhibits a rapid fault diagnosis capability. In [8], Freire *et al.* adopted an open-phase fault diagnostic method based on the

derivative of the absolute current Park's vector, which exhibits a high immunity to false alarms. In [9], Yang *et al.* presented an on-line open-phase fault diagnostic method via analysis of the neutral-point voltage characteristics. This method exhibits satisfactory fault diagnosis performance, especially for the operating conditions with low fault harmonic magnitudes, *e.g.*, light load conditions, since the fault harmonic in the neutral-point voltage results in reduced effects on sensor measurement errors and torque loads. In [10], Hang *et al.* developed a zero-sequence voltage component (ZSVC) based method to diagnose open-phase faults for PMSM drive systems. With the combined analysis of the fundamental component of the ZSVC and the initial phase angle difference of stator currents, this method can not only diagnose open-phase faults, but also discriminate fault types (electrical failures of inverter phase legs or internal stator winding ruptures). It should be noted that for both of the methods presented in [9] and [10], an accessible neutral-point of stator windings and an additional resistance network are needed, which might not be feasible in most industrial applications. Up to date, most of the existing methods focused on three-phase motor-drive systems, in which the open-phase fault results in a symmetry in the remaining two phase currents with the same magnitude and an 180-degree phase shift in between. By contrast, an asymmetry appears between the remaining four phase currents in five-phase motor-drive systems with an open-phase fault, due to the compensation action of closed-loop vector-controlled drives [11], [12]. Hence, many of these effective diagnostic approaches developed for three-phase counterparts would be invalid in five-phase PMSM drive systems.

More recently, few methods have been developed to diagnose open-phase faults in five-phase motor-drive systems. In [13], Salehifar *et al.* presented a current signal-based method to diagnose open-phase faults in a five-phase PMSM drive system via analysis of the particular characteristics of currents in a subspace $d-q$ reference frame. Since the fault localization is conducted for each phase of the motor separately, this method is inefficient during execution, and a time delay has to be considered to avoid false alarms. In [14], Trabelsi *et al.* developed a centroid-based diagnostic method of open-phase faults for five-phase PMSMs. It was found that the current locus in a subspace $\alpha\beta$ -reference frame is a point under normal condition, while it is an ellipse-like shape under open-phase fault condition. It should be noted that for the work presented in both [13] and [14], only one type of open-phase faults, *i.e.*, single-phase open faults, is taken into account. In [15], Arafat *et al.* presented an open-phase fault diagnostic method for a five-phase PMSM based on symmetrical component theory. With analysis of the magnitude and phase angle of the fundamental currents in the five symmetrical component sequences, both of the different open-phase fault types and localization of the faulted phase/phases are effectively identified. The limitation of this method comes from the fact that the phase angle of currents in the remaining phases is assumed as constant before and after the open-phase faults. In fact, both of the magnitude and phase angle of currents in the

remaining phases will change, after open-phase faults occur in the motor fed by a closed-loop vector-controlled drive with the voltage source inverter (VSI), which is adopted in most of the high-performance industrial applications [16], [17].

Differing from the previous diagnostic methods for open-phase faults in five-phase PMSM drive systems, this paper brings new contributions with further extension of the work in [18] to present a comprehensive study on diagnosis of open-phase faults for a five-phase PMSM fed by a closed-loop vector-controlled drive based on a so-called magnetic field pendulous oscillation (MFPO) technique. The basic principle of the MFPO phenomenon was originally presented in [19]. It was subsequently developed for diagnosis of rotor broken-bar faults in [20]-[22] and stator interturn faults in [23], [24] for three-phase induction machines. Conventionally, the sensing of both the phase currents and voltages is needed to monitor the resultant magnetic field affected by a broken-bar or an interturn fault. Accordingly, for the five-phase motor-drive system investigated in this paper, at least four current sensors and four voltage sensors would be needed to implement the diagnostic approach, which will increase the system cost and physical volume. On the other hand, the three-phase induction machines investigated in [19]-[24] are fed by open-loop drives. In this paper, the MFPO technique is re-developed for diagnosis of open-phase faults for a five-phase PMSM fed by a closed-loop vector-controlled drive. Moreover, in order to reduce the hardware complexity and implementation cost, a phase-locked loop (PLL) technique is developed, by which only the sensing of phase currents is required. Finally, the effectiveness of the presented diagnostic approach is verified by experimental results.

II. MFPO PHENOMENON IN PMSMS

The schematic diagram of the investigated five-phase PMSM drive system is shown in Fig. 1. It contains a five-leg VSI drive and a five-phase PMSM. The motor-drive system is operated with a closed-loop vector-controlled strategy, in which the reference stator voltages in the $d-q$ rotating reference frame are generated by the associated proportional-integral (PI) regulators based on the difference between the commanded signals, *i.e.*, the current and the speed, and their corresponding measured signals [25]. The specifications of the motor-drive system are listed in Table I. It should be noted that in order to guarantee the safety of the system when testing a faulted machine in section IV, as well as for the sake of consistency throughout this paper, the five-phase PMSM is run at a low operating point of 6 Nm at 100 r/min.

Under normal condition, the ideal five-phase currents can be expressed by eq. (1). These currents are sequentially shifted by 72 electrical degrees, *i.e.*, $2\pi/5$, from phase-A to phase-E as:

$$\left. \begin{aligned} i_a &= I_m \cdot \cos(\omega_s t) \\ i_b &= I_m \cdot \cos(\omega_s t - 2\pi/5) \\ i_c &= I_m \cdot \cos(\omega_s t - 4\pi/5) \\ i_d &= I_m \cdot \cos(\omega_s t - 6\pi/5) \\ i_e &= I_m \cdot \cos(\omega_s t - 8\pi/5) \end{aligned} \right\} \quad (1)$$

Fig. 1. Schematic diagram of the five-phase motor-drive system.

TABLE I
SPECIFICATIONS OF THE INVESTIGATED MOTOR-DRIVE SYSTEM

Parameter	Value	Parameter	Value
Supply voltage (VDC)	50	PM flux linkage (Wb)	0.037
Number of stator slots	40	d -axis inductance (mH)	0.85
Number of rotor poles	44	q -axis inductance (mH)	0.87

where, I_m is the magnitude of phase currents, ω_s is the synchronous speed in electrical rad/s. The fundamental component of the stator magnetomotive forces (MMFs) can be expressed as:

$$\left. \begin{aligned} f_a &= 1/2 \cdot N_s \cdot I_m \cdot \cos \theta \cdot \cos(\omega_s t) \\ f_b &= 1/2 \cdot N_s \cdot I_m \cdot \cos(\theta - 2\pi/5) \cdot \cos(\omega_s t - 2\pi/5) \\ f_c &= 1/2 \cdot N_s \cdot I_m \cdot \cos(\theta - 4\pi/5) \cdot \cos(\omega_s t - 4\pi/5) \\ f_d &= 1/2 \cdot N_s \cdot I_m \cdot \cos(\theta - 6\pi/5) \cdot \cos(\omega_s t - 6\pi/5) \\ f_e &= 1/2 \cdot N_s \cdot I_m \cdot \cos(\theta - 8\pi/5) \cdot \cos(\omega_s t - 8\pi/5) \end{aligned} \right\} \quad (2)$$

where, N_s is the number of effective turns per phase. The total stator MMF can be expressed as:

$$F_s = \sum_{n=a}^e f_n = 5/4 \cdot N_s \cdot I_m \cdot \cos(\theta - \omega_s t) \quad (3)$$

The total stator MMF space-vector can be expressed as:

$$\vec{F}_s = F_s \cdot e^{j\omega_s t} \quad (4)$$

As can be seen, the locus of the total stator MMF space-vector is a circle. The electromagnetic torque can be expressed as:

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

$$\vec{\psi}_s = \int (\vec{V}_s - R_s \cdot \vec{I}_s) dt \quad (6)$$

where, P is the number of rotor poles, $\vec{\psi}_s$ is the stator flux linkage space-vector, $\vec{I}_s$ is the current space-vector, $\vec{V}_s$ is the voltage space-vector, and R_s is the stator phase resistance.

Under faulty condition, assuming an open-phase fault occurred in phase-A, the stator MMF of phase-A would be zero, i.e., $f_a = 0$ in eq. (2). The total stator MMF is re-presented as:

$$F'_s = F_f \cdot \cos(\theta - \omega_s t) + F_b \cdot \cos(\theta + \omega_s t) \quad (7)$$

The total stator MMF space-vector is re-written as:

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

As can be seen, due to the open-phase fault, the resultant stator MMF space-vector, $\vec{F}'_s$, is resolved into two components, i.e., a

strong forward component rotating counter clockwise (CCW) at synchronous speed, $\vec{F}'_f$, and a weak backward component rotating clockwise (CW) also at synchronous speed but in the opposite direction, $\vec{F}'_b$. Based on eq. (6), the stator flux linkage space-vector is controlled by the action of the VSI drive through the voltage space-vector, with the current space-vector as the system state variable. Hence, the resultant current space-vector, $\vec{I}'_s$, would also be resolved into two components, i.e., a strong forward component rotating CCW at synchronous speed, $\vec{I}'_f$, and a weak backward component rotating CW also at synchronous speed, $\vec{I}'_b$, as expressed as follows:

$$\vec{I}'_s = \vec{I}'_f + \vec{I}'_b \quad (9)$$

Substituting eq. (9) into eq. (5), the torque of the faulted motor can be expressed as:

$$T'_e = 5/4 \cdot P \cdot [\vec{\psi}_s \times (\vec{I}'_f + \vec{I}'_b)] = 5/4 \cdot P \cdot (\vec{\psi}_s \times \vec{I}'_f + \vec{\psi}_s \times \vec{I}'_b) \quad (10)$$

The first term in eq. (10) represents a constant torque component, while the second term represents a torque ripple component with a frequency equal to double of the fundamental operating frequency. It is expected that the compensation action of the closed-loop vector-controlled drive would tend to reduce the torque ripple by adjusting the voltage space-vector, which will directly impact the stator flux linkage space-vector [11], [26]. Due to this adjustment, both the resultant voltage space-vector, $\vec{V}'_s$, and the resultant stator flux linkage space-vector, $\vec{\psi}'_s$, would be resolved into two components, i.e., forward components, $\vec{V}'_f$ and $\vec{\psi}'_f$, and backward components, $\vec{V}'_b$ and $\vec{\psi}'_b$, as expressed by eq. (11) and eq. (12), respectively, as follows:

$$\vec{V}'_s = \vec{V}'_f + \vec{V}'_b \quad (11)$$

$$\vec{\psi}'_s = \vec{\psi}'_f + \vec{\psi}'_b \quad (12)$$

Consequently, the torque in eq. (10) can be re-written as:

$$\begin{aligned} T'_e &= 5/4 \cdot P \cdot [(\vec{\psi}'_f \times \vec{I}'_f) \times (\vec{I}'_f + \vec{I}'_b)] \\ &= 5/4 \cdot P \cdot [(\vec{\psi}'_f \times \vec{I}'_f) + (\vec{\psi}'_f \times \vec{I}'_b) + (\vec{\psi}'_b \times \vec{I}'_f) + (\vec{\psi}'_b \times \vec{I}'_b)] \end{aligned} \quad (13)$$

The first term in eq. (13) represents a constant torque which is the main developed torque of this motor. The second term and the third term represent torque ripples with a frequency equal to double of the fundamental operating frequency. The last term represents a constant torque with the opposite direction to the main torque in the first term, which results in a reduction of the average output torque of the motor-drive system. Responding to the torque reduction, the closed-loop vector-controlled drive would increase the magnitude of the forward current space-vector, $\vec{I}'_f$, to track the reference torque.

The simulated current and torque profiles before and after the phase-A open fault are shown in Fig. 2 and Fig. 3, respectively. In this case, the fault occurs at 0.25s. As can be seen, the average torque under faulty condition is the same as that under normal condition. This phenomenon is due to the compensation action of the closed-loop vector-controlled drive by re-configuring the currents, as depicted in Fig. 2. These results verify the correctness of the previously presented analysis.

The loci of the voltage, current, and stator flux linkage

Fig. 2. Current profiles when the phase-A open fault occurs.

Fig. 3. Torque profile when the phase-A open fault occurs.

space-vectors under open-phase fault condition are depicted in Fig. 4. As can be seen, the asymmetry in the stator windings due to an open-phase fault disturbs the air-gap magnetic field, causing the air-gap magnetic field to form into two motions, *i.e.*, one motion rotates at synchronous speed as the original rotation under normal condition, while the other motion oscillates around the original synchronously rotating axis. This is the so-called “magnetic field pendulous oscillation (MFPO)” phenomenon [19], [23]. In this paper, the MFPO phenomenon is utilized to diagnose the open-phase faults for a five-phase PMSM drive system.

III. DIAGNOSIS OF OPEN-PHASE FAULTS BASED ON MFPO

As has been shown in [19]–[24], the MFPO can be observed by instantaneously monitoring the relative position of the stator voltage space-vector, $\vec{V}_s$, and the stator current space-vector, $\vec{I}_s$. However, for the investigated five-phase PMSM with ungrounded star-connected windings, at least four voltage and four current measurements are required. In order to reduce the hardware complexity and implementation cost, a PLL technique is developed, as depicted in Fig. 5 [27], [28]. As a result, only four measured phase currents are required, while these currents are already available in the closed-loop vector-controlled motor drive. In other words, no additional sensors and/or related signal conditioning circuits are needed.

The five phase currents are obtained from the four measured current signals due to the ungrounded star-connected winding configuration, *i.e.*, $\sum(i_a + i_b + i_c + i_d + i_e) = 0$. Then, the currents are transformed to the stationary α - β reference frame with the conventional utility angular position, θ , *e.g.*, $i_{\alpha 1} = I_m \cdot \cos \theta$ and $i_{\beta 1} = I_m \cdot \sin \theta$. Furthermore, these currents are transformed to the synchronously rotating d - q reference frame with the output angular position of the PLL, θ^* , instead of θ , as expressed as follows:

Fig. 4. Space-vector diagram of the closed-loop vector-controlled motor-drive system in case of an open-phase fault.

Fig. 5. Block diagram of the five-phase PLL structure.

$$\begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} = \begin{bmatrix} \cos \theta^* & \sin \theta^* \\ -\sin \theta^* & \cos \theta^* \end{bmatrix} \begin{bmatrix} i_{\alpha 1} \\ i_{\beta 1} \end{bmatrix} = \begin{bmatrix} I_m \cdot \cos(\theta^* - \theta) \\ -I_m \cdot \sin(\theta^* - \theta) \end{bmatrix} \quad (14)$$

By setting $i_{q1}=0$ as the input of the PLL, this offers immediate possibility to lock onto the utility current. It should be noted that the rotating d - q reference frame is synchronized to the fundamental output frequency of the drive. The output angular position of the PLL, θ^* , would not be affected by any oscillation caused by an open-phase fault [29]. Hence, the output angular position of the PLL, θ^* , can be used as a reference, which is rotating CCW at synchronous speed. Accordingly, the aforementioned MFPO phenomenon can be measured by the oscillation of the stator current space-vector, $\vec{I}_s$, with respect to the output angular position of the PLL, θ^* , which is defined as “MFPO angular position” as depicted in Fig. 6.

The presented diagnostic approach of open-phase faults includes three steps as follows: 1) Detection of any open-phase fault from normal condition; 2) Classification of different types of open-phase faults. Due to the limitation of zero neutral-point current, the five-phase PMSM cannot operate under three-phase open fault condition [17]. Hence, three types of open-phase faults are investigated in this paper. Namely, these are single-phase (SP) open faults, two-adjacent-phase (TAP) open faults, and two-nonadjacent-phase (TNP) open faults; 3) Localization of the faulted phase/phases.

A. Detection of Open-Phase Faults

The stator current space-vector is obtained by the measured currents as follows:

$$\vec{I}_s(t) = 2/5 \cdot [i_a(t) + \alpha \cdot i_b(t) + \alpha^2 \cdot i_c(t) + \alpha^3 \cdot i_d(t) + \alpha^4 \cdot i_e(t)] \quad (15)$$

where, $\alpha = e^{j(2\pi/5)}$ is the complex space-vector operator. It should be noted that only fundamental components are taken into account in this paper. The MFPO angular position, $\delta(t)$, is expressed as:

Fig. 6. Re-defined MFPO in space-vector diagram.

$$\delta(t) = \angle \vec{I}_s(t) - \theta^*(t) \quad (16)$$

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

Under normal condition, the MFPO angular position, $\delta(t)$, is theoretically calculated as zero, *i.e.*, $\delta(t)=0$. By contrast, under open-phase fault condition, as aforementioned in section II, an oscillating motion appears around the original synchronously rotating axis with a frequency equal to double of the fundamental operating frequency. Hence, the MFPO angular position, $\delta(t)$, under faulty condition, can be expressed as:

$$\delta(t) = \Delta\delta_s \cdot \cos(2\omega_s \cdot t) \quad (17)$$

where, $\Delta\delta_s$ is the magnitude of the MFPO angular position waveform. The MFPO angular position, $\delta(t)$, under both normal and open-phase fault conditions, is plotted in a polar coordinate manner as shown in Fig. 7. For any point (r, δ) in these polar plots, the radius is calculated by $r(t) = |\text{Re}[\vec{I}_s(t)]|$. As can be seen, the locus/trace of the $\vec{r}(t) = r(t)\angle\delta(t)$ vector shows a straight line under normal condition, while the loci/traces show unfilled-petal shapes under open-phase fault conditions. These different shape signatures can be used for detection of open-phase faults.

B. Classification of Open-Phase Fault Types

The MFPO angular position waveforms under the conditions of the three different open-phase fault types are shown in Fig. 8. For the sake of generality, the waveform of $\delta(t)$ under normal condition is included in Fig. 8(a). The results of the magnitude of the MFPO angular position waveform, $\Delta\delta_s$, are listed in Table II.

As can be seen, the $\Delta\delta_s$ under normal condition stays almost zero [refer to Fig. 8(a)]. By contrast, under faulty condition, SP open faults have the smallest value, *i.e.*, ≈ 2.5 (refer to Table II), while TAP open faults have the largest value, *i.e.*, ≈ 15.2 . It indicates that compared to the other two types of the investigated fault scenarios, TAP open faults are the most serious faults. Moreover, the values of $\Delta\delta_s$ for each type of faults stay almost the same regardless of the faulted phase leg/legs. Hence, the significantly different values of $\Delta\delta_s$ with different open-phase fault types can be used to classify the fault types.

It should be noted that in order to be more practical, typical lower and upper bounds are set for each type of open-phase faults, which are marked in Fig. 8. If the value of $\Delta\delta_s$ is within the region between the lower and upper bounds, the specific type of open-phase faults can be identified. In addition, it is interesting to note that the MFPO angular position waveforms

Fig. 7. Polar coordinate plot (r, δ) under normal and faulty conditions.

Fig. 8. MFPO angular position waveforms with different types of open-phase faults. (a) SP faults (the result under normal condition is included). (b) TAP faults. (c) TNP faults.

TABLE II
VALUE OF $\Delta\delta_s$ FOR ALL POSSIBLE OPEN-PHASE FAULTS

SP faults	$\Delta\delta_s$	TAP faults	$\Delta\delta_s$	TNP faults	$\Delta\delta_s$
Phase-A	2.5	Phase-A&B	15.2	Phase-A&C	5.9
Phase-B	2.5	Phase-B&C	15.2	Phase-B&D	5.8
Phase-C	2.5	Phase-C&D	15.3	Phase-C&E	5.8
Phase-D	2.6	Phase-D&E	15.2	Phase-D&A	5.9
Phase-E	2.5	Phase-E&A	15.2	Phase-E&B	5.9

consist of two cyclic periods in one electrical cycle, which confirmed the second-harmonic nature of the MFPO phenomenon as previously mentioned [refer to eq. (17)].

C. Localization of the Faulted Phase/Phases

As observed in Fig. 8, for each type of open-phase faults, *e.g.*, SP faults in Fig. 8(a), there is a 72-degree phase shift between the five scenarios from phase-A fault through phase-E fault. More specifically, the MFPO angular position waveform of phase-A fault is leading that of phase-B fault by 72 degrees, and so forth. The same rule can also be observed in the other two open-phase fault types, as marked in Fig. 8(b) and (c), respectively. Hence, for each type of faults, with the knowledge of the faulted phase/phases in one of the five scenarios, the localization of the faulted phase/phases in the other four scenarios can be successfully targeted by the 72-degree phase shift.

In this paper, the challenge of the prerequisite mentioned above is overcome by the phase angle analysis of the MFPO angular position waveform with respect to the output angular position of the PLL, θ^* (refer to Fig. 5). As previously concluded, the MFPO angular position waveform alternates with a frequency equal to double of the fundamental operating frequency, while the output angular position of the PLL, θ^* , has been locked onto the utility current and synchronized to the fundamental operating frequency. Hence, the half phase angle of the MFPO angular position waveform, $\gamma/2$, will synchronize with the output angular position of the PLL, θ^* . More specifically, the angular difference between $\gamma/2$ and the θ^* at the first instant of time, *i.e.*, $\theta^*(1)$, will be constant, and is defined as follows:

$$\text{ang_dif} = \gamma/2 - \theta^*(1) \quad (18)$$

where, γ is the phase angle of the MFPO angular position waveform. The calculated values of the angular difference, *ang_dif*, for all case-studies are listed in Table III. With the specific value of *ang_dif* for each open-phase fault case-study, the localization of the faulted phase/phases can be identified.

It should be noted that in practice, typical angular regions around the specific value of *ang_dif* are set based on the results in Table III, as depicted in Fig. 9. Taking SP faults as an example, if the value of *ang_dif* is within the red region of Fig. 9(a), the faulted phase, *i.e.*, phase-A, can be identified. The same rule can also be observed in the case-studies from phase-B through phase-E faults, as well as in the case-studies of TAP and TNP faults shown in Fig. 9(b) and (c), respectively. In addition, it is interesting to note that there is also an approximate 72 difference between the results of two adjacent case-studies for each type of faults, *e.g.*, the difference between the *ang_dif* of phase-A fault and that of phase-B fault is $-4.2 - (-75.9) = 71.7 \approx 72$.

The overall open-phase fault diagnosis procedure/algorithm is shown in the flowchart of Fig. 10. It should be noted that the specific results including the magnitude of the MFPO angular position waveform, $\Delta\delta_s$, in Table II and the angular difference, *ang_dif*, in Table III, are obtained at one specific operating point. Since most of the motor-drive systems in common industrial applications, fans and pumps, *etc.*, are operated at one operating point (the so-called rated operating point), the presented diagnostic approach is effective, low-cost, and practical. On the other hand, for the motor-drive systems which have more than one operating point, *e.g.*, electric vehicles, the

TABLE III
VALUE OF *ang_dif* FOR ALL POSSIBLE OPEN-PHASE FAULTS

SP faults	<i>ang_dif</i>	TAP faults	<i>ang_dif</i>	TNP faults	<i>ang_dif</i>
Phase-A	-4.2	Phase-A&B	-51.8	Phase-A&C	10.7
Phase-B	-75.9	Phase-B&C	-124.2	Phase-B&D	-60.8
Phase-C	-148.7	Phase-C&D	-195.9	Phase-C&E	-133.7
Phase-D	-220.6	Phase-D&E	-267.9	Phase-D&A	-205.3
Phase-E	-293.4	Phase-E&A	-340.0	Phase-E&B	-277.3

Fig. 9. Typical angular regions for localization of the faulted phase/phases. (a) SP faults. (b) TAP faults. (c) TNP faults.

Fig. 10. Algorithmic flowchart of the diagnostic approach.

open-phase faults can also be successfully diagnosed using this diagnostic approach with look-up tables [30].

IV. EXPERIMENTAL VALIDATION

To validate effectiveness of the presented diagnostic approach, a five-phase motor prototype which is a dual-rotor surface-mounted PMSM with high torque density, was used for the experimental setup as shown in Fig. 11. More details can be found in [31].

Fig. 11. Test hardware setup. (a) Prototype of the five-phase PMSM. (b) Five-phase drive. (c) Test bench of the five-phase motor-drive system.

As previously analyzed, the effectiveness of the PLL is the prerequisite of the presented diagnostic approach. The measured current space-vector angle, $\angle \vec{I}_s(t)$, and the output angular position of the PLL, $\theta^*(t)$, in a certain electrical cycle are shown in Fig. 12. It should be noted that in order to illustrate the MFPO phenomenon more explicitly, the results are obtained with a TAP fault in phase-A&B. As can be seen, with the time increasing, the current space-vector angle, $\angle \vec{I}_s(t)$, increases with oscillation, while the output angular position of the PLL, $\theta^*(t)$, increases linearly without any oscillation resulting from the open-phase fault. These experimental results verify the effectiveness of the PLL.

The MFPO angular position waveforms under normal condition, as well as under SP fault in phase-A, TAP fault in phase-A&B, and TNP fault in phase-A&C, are shown in Fig. 13(a), (b), (c), and (d), respectively. The measured magnitude of the MFPO angular position waveform, $\Delta\delta_s$, and the angular difference, ang_dif , for all case-studies are listed in Table IV (in comparison with the simulation results in Table II) and Table V (in comparison with the simulation results in Table III), respectively. As can be seen, the simulation results and experimental results are in good agreement. There is a negligible discrepancy which may be due to the fact that the measurement interferences of current sensors and the saturation of the motor are not taken into account in the simulations.

It should be noted that the experimental signals in Fig. 13 are sampled in the same electrical cycle with the simulation counterparts as depicted in Fig. 8. In practice, for an on-line diagnostic approach, the signals can be sampled at any time. Hence, to further verify this approach, two more MFPO angular position waveforms under SP fault in phase-A with different sampling instants are shown in Fig. 14, viz. case-study I [sampling at 1/4 electrical cycle lagging to that in Fig. 13(b)] and case-study II [sampling at 1/2 electrical cycle lagging to that in Fig. 13(b)]. Their associated results of the fault indicators, i.e., the magnitude of the MFPO angular position waveform, $\Delta\delta_s$, and the angular difference, ang_dif , are listed in Table VI. As can be seen, both the experimental results of

Fig. 12. Validation of the effectiveness of PLL.

Fig. 13. Comparison of simulated and measured MFPO angular position waveforms. (a) Normal condition. (b) SP fault in phase-A. (c) TAP fault in phase-A&B. (d) TNP fault in phase-A&C.

TABLE IV

EXPERIMENTAL VALUE OF $\Delta\delta_s$ FOR ALL POSSIBLE OPEN-PHASE FAULTS

SP faults	$\Delta\delta_s$	TAP faults	$\Delta\delta_s$	TNP faults	$\Delta\delta_s$
Phase-A	2.9	Phase-A&B	16.7	Phase-A&C	5.6
Phase-B	2.7	Phase-B&C	17.1	Phase-B&D	5.7
Phase-C	2.8	Phase-C&D	16.6	Phase-C&E	5.5
Phase-D	2.8	Phase-D&E	16.9	Phase-D&A	5.5
Phase-E	2.7	Phase-E&A	17.2	Phase-E&B	5.6

TABLE V

EXPERIMENTAL VALUE OF ang_dif FOR ALL POSSIBLE OPEN-PHASE FAULTS

SP faults	ang_dif	TAP faults	ang_dif	TNP faults	ang_dif
Phase-A	-4.1	Phase-A&B	-53.9	Phase-A&C	10.4
Phase-B	-77.3	Phase-B&C	-127.2	Phase-B&D	-61.1
Phase-C	-147.6	Phase-C&D	-199.8	Phase-C&E	-133.8
Phase-D	-220.4	Phase-D&E	-271.0	Phase-D&A	-202.0
Phase-E	-292.4	Phase-E&A	-344.1	Phase-E&B	-276.5

Fig. 14. MFPO angular position waveforms with different sampling instants. (a) Case-study I. (b) Case-study II.

TABLE VI

COMPARISON OF FAULT INDICATORS WITH DIFFERENT SAMPLING INSTANTS

Case-studies	$\Delta\delta_s$		ang_dif	
	Simulation	Experiment	Simulation	Experiment
Origin [Fig. 13(b)]	2.5	2.9	-4.2	-4.1
Case-study I	2.5	2.8	-3.8	-4.4
Case-study II	2.5	2.8	-5.2	-4.9

case-study I and case-study II are also in good agreement with their simulation results. Moreover, the fault indicators, *i.e.*, $\Delta\delta_s$ and ang_dif , are not affected by the variation of sampling instants, which is consistent with the theoretical analysis presented in section II.

V. CONCLUSION

An on-line open-phase fault diagnostic approach based on the MFPO phenomenon for a five-phase PMSM fed by a closed-loop vector-controlled drive, was developed in this paper. The MFPO concept was introduced and demonstrated to effectively explain how the magnetic field is affected by the

open-phase faults in a five-phase motor-drive system. Based on the theoretical analysis, as well as the simulation and experimental results, the following conclusions can be inferred:

- 1) Unlike the circularly rotating magnetic field under normal condition, the open-phase fault disturbs the air-gap magnetic field, which leads it into two motion components, *i.e.*, one motion component rotates at synchronous speed, while the other motion component oscillates around the original synchronously rotating axis with a frequency equal to double of the fundamental operating frequency.
- 2) With the PLL technique, a reference can be found, *i.e.*, the output angular position of the PLL, θ^* , which would not be affected by any oscillation caused by an open-phase fault. Moreover, the hardware complexity and implementation cost of the diagnostic approach was significantly reduced. As a result, only the measurement of four phase currents is required. These currents are already available in such a motor-drive system. In other words, no additional sensors and/or related signal conditioning circuits are needed.
- 3) Different open-phase fault types, *i.e.*, SP, TAP, TNP faults, result in significantly different values of the magnitude of the MFPO angular position waveform, $\Delta\delta_s$. This phenomenon indicates that $\Delta\delta_s$ is a feasible option to be a fault indicator to detect the existence of open-phase faults and classify the open-phase fault types.
- 4) For each type of such open-phase faults, each open-phase fault case-study has a specific value of the angular difference, ang_dif , which can be utilized to localize the faulted phase/phases. More interestingly, there is an approximate 72-degree difference of the ang_dif between two adjacent case-studies for each type of open-phase faults.
- 5) The fault indicators, *i.e.*, $\Delta\delta_s$ and ang_dif , are not affected by the variation of sampling instants. Hence, the presented diagnostic approach is effective, reliable, and practical.

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