Fast and accurate open-circuit fault diagnosis method for PWM voltage source inverters in the three-phase PMSM control systems

Jun Sun¹, Min Zhu², Xinxiu Zhou¹,³, Yufei Xu² and Yi Xu²
¹Fundamental Science on Novel Inertial Instrument & Navigation System Technology Laboratory, Beihang University, Beijing 100191, China
²Shanghai Institute of Satellite Engineering, Shanghai 201109, China
³E-mail: 580927@163.com

Abstract. Traditional fault diagnosis methods for converter open-circuit faults may present poor anti-interference performance, low detection speed and high misdiagnose rate especially during the motor acceleration. In order to solve the above problem, a new converter single open-circuit faults diagnosis method is proposed in this paper. Firstly, though conducting differential operation for the current variables, the common mode interference can be removed. Based on the differential information, differential currents states observer is designed, which improves the anti-jamming performance of the diagnosis method. Secondly, to avoid misdetection, a variable fault detection threshold is designed. This kind of faults diagnosis method does not need additional sensors or hardware change, and does not require the motor phase currents to be sinusoidal. Besides, the detection index rises rapidly once the fault occurs. Therefore, the application range, detection accuracy, and fault detection speed can be improved simultaneously. Finally, experimental results are presented to demonstrate the correctness of the analysis and the validity of the proposed methods.

1. Introduction
Permanent magnet synchronous motor (PMSM) is widely applied in aerospace, electric vehicle, industrial automation etc. for its high power density, efficiency, excellent control performance, reliability and robustness [1-5]. However, different types of faults may occur in motor systems [6]. Among the faults, PWM voltage source inverter (PWM-VSI) open-circuit and the short-circuit faults can account for up to 38% in industrial drives [7]. As the short-circuit faults are pernicious for VSI, hardware protection circuits are often introduced into the motor drivers, which would transform the short-circuit faults into open-circuit faults (OCFs) [7]. Hence, more attention should be paid to OCFs.

Recently, numerous researches have been conducted on the fault diagnosis methods for inverter OCFs. They can be mainly divided into three categories: signal-based methods, data-driven methods and model-based methods. The diagnostic indexes for signal-based fault diagnosis methods [8-11] are linked to sine wave, such as mean value, average current Park vector, second harmonic components of d-q currents and so on, which surfers from the low detection rates and high the false-alarm-rate. While the data-based methods [12-15] are based on the methods of pattern recognition, such as neural networks, multi-class correlation vector machines and so on. The requirement for big data and a long time for training limit the application of those methods. The methods based on analytical model were also proposed [16-18]. In [16, 17], the observers are designed to estimate the voltage error in d-q plane.
caused by faults to diagnose faults. They have fast diagnosis speed, but its anti-jamming performance is poor due to the calculation for time derivatives of phase currents. Another model-based fault detection method is proposed in [18]. It is based on currents sliding mode observer, which avoids the calculation of derivatives and improves the noise immunity. However, this method is aimed at modular multilevel converters (MMC) and is not suitable for typical PWM voltage source inverters (PWM-VSI). Therefore, it is necessary to design a fast, accurate, noise immune and universally applicable open-circuit fault diagnosis method for PWM-VSI.

A novel OCF diagnosis method for PWM-VSI of PMSM is proposed in this paper. Firstly, a differential currents states observer is designed to estimate the motor differential currents, which eliminates the common mode interference and avoids the derivative operation for phase currents. Though comparing the evaluated differential currents with the real ones, the residual vector (detection index) can be obtained. Then, the change law of residual has been analyzed, which indicates that the size of residual would increase distinctly and the direction of the residual is related to the fault source once the OCF occurs. Fault diagnosis is achieved according to the residual vector. Furthermore, to avoid misdetection, a variable fault detection threshold is designed.

2. Proposed fault diagnosis method

2.1. A subsection

Under normal condition, the voltage equation for a three-phase PMSM driven by a PWM-VSI (see Figure 1) can be written as:

\[ u_{abc} = L_{abc} p i_{abc} + R i_{abc} + e_{abc} + u_n \]  
(1)

where, \( u_{abc} \) is the motor terminal voltage, \( u_{abc} = [u_a, u_b, u_c]^T \), they are the motor three-phase terminal voltages, \( i_{abc} \) are three-phases currents, \( i_{abc} = [i_a, i_b, i_c]^T \), \( R \) is the phase resistance, \( L \) is the inductance matrix, \( p \) is differential operator, \( L_{abc} = [L_{AA}, L_{AB}, L_{AC}; L_{AB}, L_{BB}, L_{BC}; L_{AC}, L_{BC}, L_{CC}] \), \( e_{abc} \) is phase back-EMFs, \( e_{abc} = [e_a, e_b, e_c]^T \), \( u_n \) is the voltage of motor neutral point, respectively.

Neglecting the high harmonics of inductances, Equation (1) can be simplified as:

\[ u_{abc} = R i_{abc} + (L - M) p i_{abc} + e_{abc} + u_n \]  
(2)

where, \( L \) is the average phase self-inductance, \( M \) is the mean mutual inductance, respectively.
Taking the motor phase currents as states, the state equation of the motor can be expressed as:

\[ p i_{abc} = -\frac{R_s}{L-M} i_{abc} + \frac{1}{L-M} (u_{abc} - u_a - e_{abc}) \]  \hspace{1cm} (3)

2.2. Voltage distortion after open-circuit fault

Once the OCF occurs, the motor terminal voltages would distort. Hence the fault diagnosis can be realized through detecting the terminal voltage deviation. Here, the open-circuit fault in transistor \( T_1 \) is taken as an example to illustrate the change law of terminal voltages.

When \( S_1 S_2 = 01 \), from Figure 2 it can be seen that the current circuit of phase A does not change after the fault. As in healthy system, \( i_a \) would flow through transistor \( T_2 \) (when \( i_a > 0 \)) or through diode \( D_2 \) (when \( i_a < 0 \)), and the voltage of phase A (\( u_a \)) would be set to zero approximately. Therefore, the terminal voltages would not change in this state.

\[ \Delta u_a = u_{a\text{f}} - u_{a\text{f}} \approx \begin{cases} 0 & , \ i_a < 0 \text{ or } S_1 S_2 = 01 \\ -U_{dc} & , \ i_a > 0 \text{ and } S_1 S_2 = 10 \end{cases} \]  \hspace{1cm} (4)

where, \( u_{a\text{f}} \) and \( u_{a\text{f}} \) are the output voltages of healthy and fault PWM-VSI, respectively.

According to the state-space averaging method, it can be found that the average voltage deviation in a PWM cycle can be expressed as:

\[ \Delta \bar{u}_a \approx \begin{cases} 0 & , \ i_a < 0 \\ -\bar{u}_{a\text{f}} & , \ i_a > 0 \end{cases} \]  \hspace{1cm} (5)

where, \( \bar{u}_{a\text{f}} \) is the average output voltage of healthy PWM-VSI. Neglecting the nonlinearity of the PWM-VSI, the average output voltage \( \bar{u}_{a\text{f}} \) can be approximately replaced by its reference value \( u_{a*} \), which is positive almost all the time during motor operation.

Considering the sign of the phase current is related to electrical angle of the motor, therefore the average voltage deviation would be position-dependent. Actually, in each electrical cycle, if the
electrical angle is between 180° and 360°, \( i_a \) would be positive and the average voltage deviation would be negative. This electrical angle range can be defined as fault section \( \theta_{FS} \).

Similar to the OCF in transistor \( T_1 \), the average voltage deviation under other single OCF can be characterized as shown in Table 1.

**Table 1. Change laws of terminal voltage deviation.**

| Fault source | Fault feature | sign | \( \theta_{FS} \) |
|--------------|---------------|------|-----------------|
| \( T_1 \)    | \( \Delta u_a \) | -    | (180°, 360°)    |
| \( T_2 \)    | \( \Delta u_a \) | +    | (0°, 180°)      |
| \( T_3 \)    | \( \Delta u_b \) | -    | (0°, 120°), (300°, 360°) |
| \( T_4 \)    | \( \Delta u_b \) | +    | (120°, 300°)    |
| \( T_5 \)    | \( \Delta u_c \) | -    | (60°, 240°)     |
| \( T_6 \)    | \( \Delta u_c \) | +    | (0°, 60°), (240°, 360°) |

2.3. Differential currents states observer

Considering that the voltages deviation would cause phase currents distortions, the fault detection can be realized if the phase currents for healthy motor are obtained. Actually, they can be estimated as:

\[
p \hat{i}_{abc}^* = -\frac{R_e}{L-M} \hat{i}_{abc} + \frac{1}{L-M} (\hat{u}_{abc}^* - \hat{e}_{abc})
\]

(6)

where, \( \hat{u}_{abc}^* \) is the motor the phase voltage references obtained from \( \hat{u}_d \) and \( \hat{u}_q \) (outputs of currents controllers) with inverse Park transform, \( \hat{u}_{abc}^*=[\hat{u}_{an}^*, \hat{u}_{bn}^*, \hat{u}_{cn}^*]^T \), \( \hat{i}_{abc} \) is estimated three-phases currents for healthy motor, respectively.

Form Equation (3) it can be found that the \( u_n \) is coupled with motor three-phase terminal voltages as:

\[
u_n = \frac{u_a + u_b + u_c}{3}
\]

(7)

Hence, all of the three-phase voltages and currents would distort after a single OCF, which makes the fault location difficult. Therefore, we turn to estimate the differential currents as:

\[
p \hat{i}_{123}^* = -\frac{R_e}{L-M} \hat{i}_{123} + \frac{1}{L-M} (\hat{u}_{dabc}^* - \hat{e}_{dabc})
\]

(8)

where, \( \hat{i}_{123}^*=[\hat{i}_a, -\hat{i}_b, \hat{i}_c]^T \), \( \hat{u}_{dabc}^*=[\hat{u}_{d^a}, \hat{u}_{d^b}, \hat{u}_{d^c}] \), \( \hat{e}_{dabc}=[e_a, e_b, e_c]^T \).
It can be noted that through conducting differential, the common-mode interferences can be eliminated simultaneously. For real motors, the differential currents fluctuations caused by nonlinearity of inverter, parameters inaccuracy, faults of inverter, parameters inaccuracy and noise can be equivalent to inputs fluctuations as is shown in Equation (9).

\[
p\hat{i}_{123} = -\frac{R_{s}}{L_{LM}}i_{123} + \frac{1}{L_{LM}}(u_{d-abc} - e_{d-abc} + V_{u123} + f_{123})
\]

(9)

where, \(i_{123}\) and \(u_{d-abc}\) are the real motor differential currents and line voltages, \(\Delta u_{123}\) is the line voltage deviation caused the fault, \(\Delta u_{123} = [\Delta u_{a} - \Delta u_{b}, \Delta u_{a} - \Delta u_{c}, \Delta u_{b} - \Delta u_{c}]\), \(f_{123}\) is the equivalent inputs fluctuations caused by model inaccuracy, respectively.

Assuming that the sampling period (i.e. PWM cycle) is \(T\), Equation (9) can be discretized as:

\[
p\hat{i}_{123}(k+1) = e^{-\frac{R_{s}}{L_{LM}}}i_{123}(k) + \frac{1-e^{-\frac{R_{s}}{L_{LM}}}}{R_{s}}(u_{123}(k) + V_{u123}(k) + f_{123}(k))
\]

(10)

where, \(u_{123} = u_{d-abc} - e_{d-abc}\), \(k\) is the sample point, respectively.

Therefore, the healthy observer can be designed as:

\[
p\hat{i}_{123}(k+1) = e^{-\frac{R_{s}}{L_{LM}}}i_{123}(k) + \frac{1-e^{-\frac{R_{s}}{L_{LM}}}}{R_{s}}u_{123}(k)
\]

(11)

where, \(\hat{i}_{123}\) are the estimated value of the differential currents of motor in healthy system.

It is note-worth that the input term \(u_{123}\) consists with the line voltage references and back-EMFs. The former can be obtained by conducting differential operate for three-phase voltage references, while the later can be estimated in real-time with electrical speed \(\omega_{e}\), electrical angel \(\theta_{e}\) and the back EMF waveforms functions (measured beforehand) [19].

During the motor operation, motor parameter errors, calculation error and the noises would degrade the estimation accuracy. Therefore, feedbacks should be introduced into the observer as:

\[
p\hat{i}_{123}(k+1) = e^{-\frac{R_{s}}{L_{LM}}}i_{123}(k) + (1-e^{-\frac{R_{s}}{L_{LM}}})/R_{s}\cdot u_{123}(k)+F_{1}(i_{123}(k)-\hat{i}_{123}(k))
\]

(12)

where, \(F\) is the feedback coefficient. In practice, the closed-loop poles of an observer should be assigned to 3~10 times faster than open loop poles. Based on this principle, \(F\) can be determined.

2.4. Residual analysis

Subtracting Equation (12) from Equation (10), the residual equation can be obtained as:

\[
p\hat{r}_{123}(k+1) = (e^{-\frac{R_{s}}{L_{LM}}-F})r_{123}(k) + \frac{1-e^{-\frac{R_{s}}{L_{LM}}}}{R_{s}}\Delta u_{123}(k)\approx A\cdot r_{123}(k)+B\cdot \Delta u_{123}(k)
\]

(13)

where, \(r_{123} = i_{123} - \hat{i}_{123}\). It should be noticed that the estimated errors caused by model inaccuracy are small for the closed-loop observe, therefore the corresponding terms are neglected in Equation (13).

By \(z\)-transformation, the discrete transfer functions from voltage errors to residuals are obtained as:

\[
H_{q}(z) = \frac{R_{s}(z)}{\Delta U_{q}(z)} = \frac{B}{z-A}, \quad q = 1, 2, 3
\]

(14)

where, \(R(z)\) and \(\Delta U(z)\) are the \(z\) transformations of residuals and differential voltage increments.

It can be found that the three transfer functions \(H_{1}(z), H_{2}(z)\) and \(H_{3}(z)\) are exactly same to each other and have the characteristics of first-order inertia link, which enables the residuals track the voltage deviations with a short rising delay.

From Equation (13) it can be found that when the transistor \(T_1\) is open, once the electrical angle enters into the fault section listed in Table 1, the residuals \(r_1\) and \(r_2\) would be negative, and they are equal to each other. While \(r_1\) would be still approximate zero. Hence, the unit directional vector can be derived as:
\[ \mathbf{r} = \begin{bmatrix} r_1, r_2, r_3 \end{bmatrix}^T = \begin{bmatrix} \frac{-\sqrt{2}}{2}, -\frac{-\sqrt{2}}{2}, 0 \end{bmatrix} \]  

where, \( \mathbf{r} = [r_1, r_2, r_3]^T \), \( ||\mathbf{r}|| \) is the modulus of residual vector \( \mathbf{r} \), respectively.

Similar to the OCF in transistor \( T_1 \), the unit directional vectors of residual under different single OCF can be obtained as shown in Table 2.

| Fault source | Fault Feature | sign | Directional Vector |
|--------------|---------------|------|-------------------|
| \( T_1 \)    | \( \Delta \bar{u}_a \) | -    | \( a_1^T = (-1, -1, 0)/\sqrt{2} \) |
| \( T_2 \)    | \( \Delta \bar{u}_a \) | +    | \( a_2^T = (1, 1, 0)/\sqrt{2} \) |
| \( T_3 \)    | \( \Delta \bar{u}_b \) | -    | \( a_3^T = (-1, 1, 0)/\sqrt{2} \) |
| \( T_4 \)    | \( \Delta \bar{u}_b \) | +    | \( a_4^T = (1, 1, 0)/\sqrt{2} \) |
| \( T_5 \)    | \( \Delta \bar{u}_c \) | -    | \( a_5^T = (1, 0, 1)/\sqrt{2} \) |
| \( T_6 \)    | \( \Delta \bar{u}_c \) | +    | \( a_6^T = (0, -1, 1)/\sqrt{2} \) |

**2.5. Fault detection and location**

The block diagram of the fault detect method can be described as Figure 4, where \( \mathbf{u}_{abc}^* = [\mathbf{u}_{m}^*, \mathbf{u}_{bc}^*, \mathbf{u}_{abc}^*]^T \), \( \mathbf{u}_{aber} = [\mathbf{u}_{m}, \mathbf{u}_{bc}, \mathbf{u}_{abc}]^T \), respectively. Considering that the saturation characteristic exists in the PWM-VSI, therefore the “Saturation Characteristic” block is introduced in Figure 4. Besides, to improve the anti-interference ability of this method, the low pass filters are introduced into the system as well. The cut frequency can be set as \( f_c = 5 \cdot (P_{or}/2\pi) \cdot f_{PWM}^{1/2} \), \( P \) is the pole pairs of the motor, is the frequency of PWM, respectively.

![Figure 4. The block diagram of proposed method.](image)

In Figure 4, the ‘Fault Detection’ is achieved by comparing the modulus of the residual vector with the threshold. The system would be regarded as faulty once the modulus exceeds the threshold value. Considering that the current error relates to phase current amplitude, a variable fault detection threshold is designed to avoid misdetection:

\[ Th = Th_0 + k \cdot \mathbf{i}_{123} \cdot P \]  

where, \( Th_0 \) is a constant set to avoid false alarm caused by random errors, \( ||\mathbf{i}_{123}|| \) is the modulus of differential current matrix, \( k \) is a constant coefficient between 0 and 1, respectively. The constant \( Th_0 \) and \( k \) can be obtained by tuning under extreme situations in practice.

Once the fault is detected, the ‘Location’ function would start to calculate the distance between the unit directional vector of residual and the six template vectors listed in Table 2, and locate the fault source according to the minimal-distance principle.
3. Experimental tests

3.1. Experimental setups

To verify the proposed method, a series of tests have been implemented. The parameters of the motor control system (see Figure 5) are presented in Table 3. The motor is drove by a carrier-based PWM-VSI. Its load is provided by a magnetic powder brake and the load level equivalents to 30% of the rated torque. In the tests, the OCF is performed by removing the gate signals of the ‘faulty’ transistor with the antiparallel diodes still connected. The feedback coefficient $F$ for Equation (12) is set to 0.2 while the constant coefficient $T_{th}$ and $k$ for Equation (16) are set to be 0.10 and 0.30, respectively.

![Experimental platform](image)

**Figure 5.** Experimental platform.

| Parameters                   | Unit | Value       |
|------------------------------|------|-------------|
| DC source                    | V    | 220         |
| Rated Output Torque          | N-m  | 10          |
| Rated rotor speed            | rpm  | 1200        |
| Flux linkage                 | Wb   | 0.1402      |
| Peak Stator Current          | A    | 40          |
| Phase Resistance             | Ω    | 0.67        |
| Phase Inductance             | mH   | 2.1         |
| Mutual Inductance            | mH   | -1.0        |
| Pole Pairs                   |      | 2           |
| PWM Frequency                | kHz  | 10          |
| Sample Time                  | s    | $1\times10^{-4}$ |

3.2. Experimental results

3.2.1. Test during Motor Constant Speed Operation. In this test, the motor is accelerated to the rated speed, and then is controlled to operate at rated speed. The switching signal of transistor $T_2$ is disabled at $t=0.1s$. The experimental results are displayed in Figure 6.
The experimental results are in accordance with the theoretical analysis. Before the fault, the phase currents approximate sinusoidal (see Figure 6 (a)), and the differential currents of motor are basically consistent with those estimated by observer (see Figure 6 (d), (e) and (f)). Therefore the amplitudes of residuals are small under healthy condition (Figure 6 (g)). But after the fault, the phase currents distort distinctly when \( i_3 \) is negative. And the differential currents \( i_1 \) and \( i_2 \) deviate from their real values, respectively. However, the differential current \( i_3 \) is still consistent with its evaluated value basically though the phase currents are not sinusoidal any more. As analysed in Section 2.3, the unit directional vector of residual is near to the template vector \( \alpha_l \) (see Figure 6 (g)) when the electric angle enters the fault section. And the modulus of residual vector quickly exceed beyond the threshold (see Figure 6 (h)) in fault section. The diagnosis results are shown in Figure 6 (i), which demonstrated the validity of proposed method.

Besides, the detection time is about 2.1ms, which also shows the rapidity of the proposed method.

3.2.2. Tests during Motor Acceleration. In this test, the reference speed is set to 1200r/min, and the fault occurred at \( t=0.2s \) (during the motor acceleration). Figure 7 shows the experimental results.

From Figure 7, it can be found that the change laws of residuals are the same whether the motor changes speed or not, and the detection are correct. However, the fault detection time is 30.6ms. It is much longer than that in the previous test. This is because that the detection delay is affected by the electrical angle when the fault occurs. As mentioned in Section 2.2, the mean terminal voltage deviation \( \Delta U \) is non-zero only when the motor electrical angle is within the range listed in Table 1. Hence, the fault detection may be delayed, but not more than half an electrical cycle.

However, it should be noticed that, during the delay period, the phase currents are still symmetrical sinusoidal (Figure 7 (a)), which means that the output torque of the motor is not affected due to the fault. This can be also found from Figure 7 (b) (the change rate of the rotor speed is nearly unchanged during the delay period). Hence, the performance of the motor will not deteriorate due to the delay. Therefore, this kind of detection delay can be neglected when calculating the detection time. The corrected detection time is 2.3ms, which is close to that measured in the previous experiment.
3.2.3. Robustness Testing. In order to test the robustness the proposed method, the parameters $R_s$, L and M used in the observer are deviated from their measured values. Specifically, $R_s$ is increased by 10%, while L and M are reduced by 20%. Other experimental settings are the same as test in Section 3.2.1. The results are presented in Figure 8. Though the modulus of residual vector is lager that in the test presented in Section 3.2.1, misdetection does not happen owing to the closed-loop observation and adaptive threshold. Therefore, the proposed method is robust.

4. Conclusions
Open-circuit fault occurs in PWM-VSI may not only degrade the control performance of PMSM, but lead to catastrophic accidents in extreme circumstances. To guarantee the high reliability and safety of the motor drive, a general, fast and accurate open-circuit fault diagnosis method is proposed in this paper. This method is based on differential currents state observer. With the designed observer, common-mode interference is removed, which improves the accuracy of differential current distortion estimation caused. According to the distortions, fault detection and location can be realized easily. To improve its robustness, feedbacks are introduced into the observer, and adaptive detection threshold are designed. This proposed method is effective whether the motor speed is constant or not, and it does not requires additional sensors or hardware change. Therefore, this method has wide range of application. Besides, it also has fast detection speed, high accuracy and strong robustness. The validity and the superiority of the proposed methods have been demonstrated by experiments.

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