Similarity Analysis-Based Diagnosis Method for Open-Circuit Faults of Inverters in PMSM Drive Systems

Tao Chen and Yuedou Pan*
School of Automation & Electrical Engineering, University of Science and Technology Beijing, Beijing 100083, China
*Corresponding author’s e-mail: ydpan@ustb.edu.cn

Abstract. A fast, real-time and similarity analysis-based diagnosis method for open-circuit faults in three-phase voltage-source inverters is proposed. The proposed method is based on the mixed logical dynamic (MLD) model of the PMSM drive system to simulate three-phase currents under different faulty conditions, and the Pearson correlation coefficients (PCCs) are used to measure the similarity between the simulated fault types and the actual one, then the fault detection and isolation can be achieved according to the characteristics of PCCs under different faulty conditions. The proposed method only needs to use the current sensors existing in the closed-loop system to measure the currents for fault diagnosis, and can detect the fault within one current fundamental wave period. Simulation results verify the effectiveness of the proposed method.

1. Introduction
Three-phase voltage-source inverters have been widely used in many motor drive systems. Insulated gate bipolar transistors (IGBTs) and other power devices that make up the inverters work in high voltage and high current for a long time are prone to failure. Statistics show that about 38% of the faults in the drive systems are caused by power device faults [1].

The faults of inverters are mainly divided into open-circuit faults and short-circuit faults. Generally, hardware protection circuits are designed to deal with short-circuit faults in the system [2]. Most methods for the open-circuit faults of inverters use the output current or voltage signals to diagnosis, which can be summarized as current-based methods and voltage-based methods. Current-based methods do not require additional sensors and are not susceptible to system parameters. For example, Peuget et al. [3] presented a current vector trajectory analysis method to detect open-circuit faults by analyzing the characteristics of the current vector and calculating its trajectory slope, and then the fault can be localized based on the current polarity. The average current Park vector method is proposed in [4], and the normalized current dc-components method is used to diagnosis open-circuit faults in [5]. In [6], the concept of allelic points and corresponding functions are proposed to describe the symmetry of the voltage source inverter physical topology for open-circuit fault diagnosis of the power switches. In [7], a fault diagnosis method based on probability density analysis of the sampling currents is presented for open-circuit fault detection and isolation. The diagnosis time of the above two methods is about 1/4 of the current fundamental wave period.

Compared with current-based methods, voltage-based methods can diagnose the inverter faults faster, but additional voltage sensors or hardware circuits are needed. In [8], a voltage model analysis method is investigated to reduce the detection time. By directly comparing the measured voltage with the reference voltage derived from the given pulse width modulation (PWM) signals, the method can
quickly diagnose and localize the fault of the inverter, and the diagnosis time is about 1/4 of the current fundamental wave period. Karimi et al. [9] presented a fast fault diagnosis method based on field-programmable gate array (FPGA) in wind energy conversion systems, which can minimize the time interval between fault occurrence and diagnosis, and can detect the fault within 10 μs, but the hardware of the method is complex and the cost is high.

In addition, some advanced algorithms such as neural network [10], fuzzy logic [11], support vector machine [12], random forests [13] and machine learning [14] are also applied to current-based methods and voltage-based methods for open-circuit faults diagnosis. These methods do not require a system model and are highly flexible, however, they need a large amount of calculation and are too complex to implement, and the diagnosis time is usually longer than one current fundamental wave period.

This paper proposes an open-circuit fault diagnosis method of three-phase voltage-source inverters based on similarity analysis. The presented method has the features of avoiding the use of extra sensors and fast diagnosis speed, and can detect the open-circuit fault within one current fundamental wave period.

Figure 1. The structure of the PMSM drive system with the proposed fault diagnosis scheme.

2. Fault current simulation model for three-phase voltage-source inverters

The structure of the permanent magnet synchronous motor (PMSM) drive system fed by a three-phase voltage-source inverter with the proposed fault diagnosis scheme is shown in figure 1. It is defined that the currents flowing into the winding are positive. The topology of the PMSM system is controlled by switching signals. Different switching modes correspond to different circuit topologies, which makes the current evolution paths different, thus forming a typical hybrid system. The mixed logical dynamic (MLD) model embeds the discrete events of the hybrid system into the differential equations, which can take into account the control and condition changes of the circuit, so the system can be described more accurately. Define an auxiliary logical variable $\delta_k$ ($k = a, b, c$) as the current flow direction, $\delta_k = 1$ means $i_k > 0$, and $\delta_k = 0$ means $i_k \leq 0$. Meanwhile, $s_j$ ($j = 1-6$) represent the switching signals of IGBT $T_1$–$T_6$, $s_j = 1$ means $T_j$ is on, and $s_j = 0$ means $T_j$ is off. Therefore, three-phase voltages between windings and ground can be expressed as follows:

$$
\begin{align*}
\begin{pmatrix}
u_{ag} \\
u_{bg} \\
u_{cg}
\end{pmatrix} &= \begin{pmatrix}
\bar{x}_a(s_a + \delta_a) \\
\bar{x}_b(s_b + \delta_b) \\
\bar{x}_c(s_c + \delta_c)
\end{pmatrix} V_{dc}
\end{align*}
$$

where $V_{dc}$ is the dc-bus voltage; $\nu_{ag}, \nu_{bg}, \nu_{cg}$ are the three-phase voltages between windings and ground.

According to the Kirchhoff’s law, the three-phase voltages between windings and neutral point $n$ can be describe as
\[
\begin{bmatrix}
u_{an} \\
u_{bn} \\
u_{cn}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
u_{ag} \\
u_{bg} \\
u_{cg}
\end{bmatrix}
\]

(2)

where \( u_{an}, u_{bn}, u_{cn} \) are the three-phase voltages between windings and neutral point \( n \).

For the inverter-PMSM system shown in figure 1, the MLD model are obtained as follows:

\[
\begin{align*}
\frac{di_a}{dt} &= -\frac{R}{L}i_a - \frac{1}{L}e_a + \frac{V_{de}}{3L}\eta_a \\
\frac{di_b}{dt} &= -\frac{R}{L}i_b - \frac{1}{L}e_b + \frac{V_{de}}{3L}\eta_b \\
\frac{di_c}{dt} &= -\frac{R}{L}i_c - \frac{1}{L}e_c + \frac{V_{de}}{3L}\eta_c
\end{align*}
\]

(3)

\[
\begin{bmatrix}
\eta_a \\
\eta_b \\
\eta_c
\end{bmatrix} = \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
\bar{s}_2(s_1 + \delta_a) \\
\bar{s}_4(s_1 + \delta_b) \\
\bar{s}_6(s_1 + \delta_c)
\end{bmatrix}
\]

(4)

where \( i_a, i_b, i_c \) are the phase currents; \( e_a, e_b, e_c \) are the back electromotive forces; \( R \) is the stator winding resistance, and \( L \) is the stator winding inductance; \( \eta_a, \eta_b, \eta_c \) are the discrete input variables.

Therefore, the fault current simulation model for three-phase voltage-source inverters is established as follows:

\[
\begin{align*}
\frac{d\bar{I}_a}{dt} &= -\frac{R}{L}\bar{I}_a - \frac{1}{L}e_a + \frac{V_{de}}{3L}\eta'_a \\
\frac{d\bar{I}_b}{dt} &= -\frac{R}{L}I_b - \frac{1}{L}e_b + \frac{V_{de}}{3L}\eta'_b \\
\frac{d\bar{I}_c}{dt} &= -\frac{R}{L}\bar{I}_c - \frac{1}{L}e_c + \frac{V_{de}}{3L}\eta'_c
\end{align*}
\]

(5)

where \( \bar{I}_a, \bar{I}_b, \bar{I}_c \) are the simulated currents; \( \eta'_a, \eta'_b, \eta'_c \) are the discrete input variables of the simulated fault type.

3. Proposed fault diagnosis method

The proposed fault diagnosis method includes three steps: fault current simulation, fault features extraction, fault detection and isolation.

3.1. Fault current simulation

A sliding window is designed to obtain the measured current data and simulated current data for fault diagnosis. The window length \( N \) is selected as a current fundamental period, which is defined as follows:

\[
N = \frac{2\pi}{p\omega_m T_s}
\]

(6)

where \( p \) is the number of pole pairs, \( \omega_m \) is the speed reference (rad/s), and \( T_s \) is the sampling period.

Considering the six types of single switch fault and three types of single leg fault of the inverter, the simulated fault currents of these nine fault types can be given by

\[
I_n = f(e_a, \delta_e | F_n) \quad (n = 1 - 9)
\]

(7)

where \( I = [i_{a1}, \ldots, i_{aN}, i_{b1}, \ldots, i_{bN}, i_{c1}, \ldots, i_{cN}] \), F1 – F9 represent the nine fault types.
3.2. Fault features extraction
The Pearson correlation coefficient (PCC) is used to measure the similarity between the simulated fault types and the actual one. The calculation method of the PCC is defined as follows:

\[
\rho_n(p, q) = \frac{\sum_{i=1}^{N}(p_i - \bar{p})(q_i - \bar{q})}{\sqrt{\left(\sum_{i=1}^{N}(p_i - \bar{p})^2\right) \left(\sum_{i=1}^{N}(q_i - \bar{q})^2\right)}}
\]

And define the average value of PCCs as

\[
\rho_{\text{aver}} = \frac{1}{9} \sum_{n=1}^{9} \rho_n
\]

3.3. Fault detection and isolation
Under the healthy condition, at the moment when the simulated fault acts on the model, the data generated by the fault current simulation model is different from the measured data. While the data generated at other times is the same as the measured data, and the simulated fault action time is far less than one current fundamental wave period, so the PCCs are all greater than 0.5 and less than 1 under the healthy condition, namely, \(0.5 \leq \rho_{\text{aver}} < 1\).

When an open-circuit fault occurs to the inverter, such as T1 fault, the simulated fault type F1 is the same as the actual one, and the other simulated fault types are different from the actual one, so that \(\rho_{\text{aver}} < 0.5\), and \(\max\{\rho_n\} = \rho_1 = 1\).

Therefore, the fault detection variable \(\text{FaultFlag}\) and the fault isolation variable \(\text{FaultType}\) can be defined as follows:

\[
\text{FaultFlag} = \begin{cases} 
0, & 0.5 \leq \rho_{\text{aver}} < 1 \\
1, & \rho_{\text{aver}} < 0.5 
\end{cases}
\]

\[
\text{FaultType} = \begin{cases} 
0, & 0.5 \leq \rho_{\text{aver}} < 1 \\
x, & \rho_{\text{aver}} < 0.5 \text{ and } \max\{\rho_n\} = \rho_x = 1 
\end{cases}
\]

The proposed fault diagnosis principle is shown as table 1.

| State     | Pearson correlation coefficients (PCCs) | Faulty switches | Fault type |
|-----------|----------------------------------------|----------------|------------|
| Healthy   | 0.5 \leq \rho_{\text{aver}} < 1       | No             | F0         |
|           | \(\max\{\rho_n\} = \rho_1 = 1\)       | T1             | F1         |
|           | \(\max\{\rho_n\} = \rho_2 = 1\)       | T2             | F2         |
|           | \(\max\{\rho_n\} = \rho_3 = 1\)       | T3             | F3         |
|           | \(\max\{\rho_n\} = \rho_4 = 1\)       | T4             | F4         |
| Fault     | \rho_{\text{aver}} < 0.5               |                |            |
|           | \(\max\{\rho_n\} = \rho_5 = 1\)       | T5             | F5         |
|           | \(\max\{\rho_n\} = \rho_6 = 1\)       | T6             | F6         |
|           | \(\max\{\rho_n\} = \rho_7 = 1\)       | T1, T2         | F7         |
|           | \(\max\{\rho_n\} = \rho_8 = 1\)       | T3, T4         | F8         |
|           | \(\max\{\rho_n\} = \rho_9 = 1\)       | T5, T6         | F9         |

In table 1, \(\approx\) means the values on both sides are close, which can be described as (12), where \(\epsilon\) is close to zero. In this letter, \(\epsilon\) is set equal to 0.15.

\[
x = y \Leftrightarrow |x - y| < \epsilon
\]
4. Simulation Results

The simulation model of the proposed fault diagnosis method was built in the Matlab/Simulink environment, and the rotor-field-oriented vector control strategy was applied to the control algorithm of the PMSM. The parameters related to the test motor are listed as: rated power 1.5 kW, rated torque 6.0 N•m, rated current 6.0 A, stator phase resistance 1.21 Ω, $d$-axis and $q$-axis inductance 12.5 mH, back electromotive force coefficient 65 V/krpm. The dc-bus voltage is 311 V and the reference speed is 1000 r/min with 2 N•m load. The three-phase voltage-source inverter was running with a switching frequency of 10 kHz.

Fault diagnosis: T2 fails

![Phase currents](image1)

![PCCs](image2)

![Diagnostic Variables](image3)

Fault diagnosis: T3, T4 fail

![Phase currents](image4)

![PCCs](image5)

![Diagnostic Variables](image6)

Figure 2 shows the time-domain waveforms of the motor phase currents and the PCCs, together with the diagnostic variables for a single fault (T2 fails), and figure 3 shows that for a multiple fault in the same leg (T3 and T4 fail). From these simulation results, it can be seen that the PCCs are all greater than 0.5 and the diagnostic variables are null under normal operating conditions. When an open-circuit fault occurs, most of the PCCs decrease rapidly to less than 0.5, or even become negative, and only one of them increases to close to 1, then the fault can be detected and isolated according to table 1.
5. Conclusions
A simple and fast open-circuit fault detection and isolation method of three-phase voltage-source inverter based on similarity analysis is proposed in this paper. The presented method uses the MLD model of the PMSM drive system to simulate different fault types on line, and uses the PCC to measure the similarity between the simulated fault types and the actual one, so as to achieve fault diagnosis. The presented method has the features of avoiding the use of extra sensors and fast diagnosis speed, and can detect the open-circuit fault within one current fundamental wave period.

Acknowledgments
This work was supported by the National Key R&D Program of China, under Grant 2019YFB1309900.

References
[1] Fuchs, F.W. (2003) Some diagnosis methods for voltage source inverters invariable speed drives with induction machines-a survey. In: Proc. IEEE Industrial Electronics. Roanoke. pp. 1378–1385.
[2] Lu, B., Sharma, S.K. (2009) A literature review of IGBT fault diagnostic and protection methods for power inverters. IEEE Trans. Ind. Appl., 45: 1770–1777.
[3] Peugeot, R., Courtine, S., Rognon, J. (1998) Fault detection and isolation on a PWM inverter by knowledge-based model. IEEE Trans. Ind. Applicat., 34: 1318-1326.
[4] Mendes, A. M. S., Cardoso, A. J. M. (1999) Voltage source inverter fault diagnosis in variable speed AC drives by the average current Park’s vector approach. In: IEEE International Electric Machines and Drives Conference. Seattle. pp. 704–706.
[5] Sleszynski, W., Nieznanski, J., Ciechowski, A. (2009) Open-transistor fault diagnostics in voltage-source inverters by analyzing the load currents. IEEE Trans. Ind. Electron., 56: 4681–4688.
[6] Wu, F., Zhao, J. (2016) A real-time multiple open-circuit fault diagnosis method in voltage-source-inverter fed vector controlled drives. IEEE Trans. Power Electron., 31: 1425-1437.
[7] Zhou, D., Li, Y., Zhao, J., Wu, F., Luo, H. (2017) An embedded closed-loop fault-tolerant control scheme for nonredundant VSI-fed induction motor drives. IEEE Trans. Power Electron., 32: 3731-3740.
[8] De Araujo Ribeiro, R. L., Jacobina, C. B., Da Silva E. R. C., Lima, A. M. N. (2004) Fault-tolerant voltage-fed PWM inverter AC motor drive systems. IEEE Trans. Industrial Electron., 51: 439-446.
[9] Karimi, S., Pour, P., Saadate, S. (2009) Fast power switch failure detection for fault tolerant voltage source inverters using FPGA. IET Power Electron., 2: 346–354.
[10] Sobanski, P., Kaminski, M. (2019) Application of artificial neural networks for transistor open-circuit fault diagnosis in three-phase rectifiers. IET Power Electron., 12: 2189-2200.
[11] Yan, H., Xu, Y., Cai, F. (2019) PWM-VSI fault diagnosis for PMSM drive based on fuzzy logic approach. IEEE Trans. Power Electron., 34: 759–768.
[12] Hu, Z.K., Gui, W. H., Yang, C. H., Deng, P. C., Ding, S.X. (2011) Fault classification method for inverter based on hybrid support vector machines and wavelet analysis. Int. J. Control Automat. Syst., 9: 797–804.
[13] Kou, L., Liu, C., Cai, G., Zhou, J., Yuan, Q., Pang, S. (2020) Fault diagnosis for open-circuit faults in NPC inverter based on knowledge-driven and data-driven approaches. IET Power Electron., 13: 1236-1245.
[14] Abul Masrur, M., Chen, Z., Murphy, Y. (2010) Intelligent diagnosis of open and short circuit faults in electric drive inverters for real-time applications. IET Power Electron., 3: 279–291.