Open-switch Fault Detection and Fault Localization in PMSM Drives Through Current Waveform Analysis

Jae-Hwan SONG and Kyeong-Hwa KIM*

Dept. of Electrical and Information Eng., Seoul National Univ. of Science and Tech., 232 Gongneung-ro, Nowon-gu, Seoul 01811 Korea

*Corresponding author

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Abstract. To improve the reliability in inverter-fed permanent magnet synchronous motor (PMSM) drive systems, this paper presents a simple on-line fault detection and faulty switch localization algorithm in the presence of simultaneous triple open-switch. The open-switch faults are first categorized as seven fault groups to identify the location of open-switch effectively. Since each fault group develops distinctive fault signature, an exact localization of faulty switch is possible in the proposed scheme in a straightforward and simple way. In addition, the proposed scheme can be easily employed in commercial industrial drive systems without additional equipment. The effectiveness of the proposed open-switch fault detection and faulty switch localization algorithm is verified through comparative simulations under various fault conditions.

Introduction

A fault in automation process causes the safety problem and harmful damage in industrial systems. Due to this reason, the reliability and safety issues are more and more important in electric vehicle, railway system, medical and military applications. As PWM inverter-fed permanent magnet synchronous motor (PMSM) is utilized in a wide range of drive applications such as machine tools, industrial process, and transportation recently, the reliability in motor drive systems has been considered as one of the major factors.

Almost 38% failure of the motor drive system is found in the power converter and the most of faults occur in the power switches. The power converter failures can be a critical factor to the overall drive system, leading to system shutdowns. The failure of switching devices is categorized as short-circuit fault and open-circuit fault. The short-circuit fault often yields the most critical accidents in the drive system and requires immediate action to shut down the system. On the contrary, even though the open-circuit fault does not cause critical system failure, it continuously gives a harmful effect and stress on the entire drive system such as the converter module or other components. Due to this reason, many researches have been studied concerning the diagnosis of open-switch fault.

In order to make the detection algorithm independent of operating conditions, a method using the average absolute values of normalized currents has been presented [1], [2]. This scheme uses the Park’s vector modulus to obtain the normalization current. As an alternative fault detection method, a voltage-based method has been studied for open-switch fault detection [3], in which the reference and measured values are compared to search the fault occurrence. However, to apply this scheme, a careful calibration has to be conducted in order to minimize the voltage errors which cause false alarm. Another fault diagnosis uses an observer-based technique [4].

To improve the reliability in inverter-fed PMSM drive system, this paper presents open-switch fault detection and fault localization through current waveform analysis in which moving filter-based current signals are employed to detect the open-switch fault. Moreover, the various open-switch faults are categorized as seven fault groups to effectively localize the faulty switches. The effectiveness of the proposed open-switch fault detection and faulty switch localization schemes are verified through comparative simulations using the PSIM software.
**Proposed Fault Detection and Localization Scheme**

The proposed fault detection and localization algorithms use the information on current waveforms without extra detection hardware. To reduce the fault detection time, the moving filter-based algorithm is implemented. The moving filter is employed to determine the normalized RMS currents. Figure 1 represents the proposed fault detection algorithm for inverter open-switch. First, to determine the moving filter-based RMS phase currents $I_{n,\text{rms}}$, the squared phase currents $i^2_{\alpha}$, $i^2_{\beta}$, and $i^2_{c}$ are processed through the moving filter. Then, the magnitude of current $I_{\text{m}}$ is calculated by using the filtered $q$-axis and $d$-axis currents. By using $I_{n,\text{rms}}$ and $I_{\text{m}}$ information, the normalized RMS current $I_{n,M}$ can be obtained. A fault detection variable is defined as the difference between the normalized RMS current and nominal sinusoidal RMS current as follows:

$$f_n = I_{n,M} - N_{\text{rms}} \cdot$$

(1)

where $f_n$ is a fault detection variable and $N_{\text{rms}} = 1/\sqrt{2}$ for the nominal sinusoidal current. In the normal operating condition without fault, $f_n$ is maintained to zero. This detection variable $f_n$ is consistently monitored to detect an abnormal condition of inverter switches. When the detection variable deviates from zero due to the open-switch fault, the fault occurrence can be detected by setting the variable $F_{\text{flag}}$ to one. To avoid the false alarm, if the count variable $F_{\text{count}}$ is increased to more than 10, the variable $F_{\text{status}}$ is set to one. As soon as the variable $F_{\text{status}}$ is set to one, the operating mode is changed to the fault localization algorithm to search the faulty switches.

![Figure 1. Proposed fault detection algorithm for inverter open-switch.](image)

The purpose of fault localization algorithm is to find out faulty switch by main controller without human inference through observing only the current waveforms. To effectively identify the location of faulty switches, the open-switch faults are categorized as seven groups as shown in Table 1. Each fault group denotes different faulty switches according to the number and position of faulty switches, respectively. Because the fault signature is distinct according to each fault group, each group uses a different fault localization algorithm to find out the faulty switches exactly. Figure 2(a) shows the proposed fault group identification algorithm where $Q_{\text{NZC}}$ denotes the number of non-zero cycles in each phase current. For example, during the normal condition, all three phase currents have positive current duration as well as negative current duration, yield $Q_{\text{NZC}} = 6$. However, this value is decreased under the open-switch faults depending on the number of faulty switches, that is, fault group. As soon as the fault group is determined, the faulty switches are identified by using the faulty switch identification algorithm. Figure 2(b) shows the proposed faulty switch identification algorithm in the fault group FG1.
Table 1. Fault group for inverter open-switch.

<table>
<thead>
<tr>
<th>Fault group</th>
<th>Faulty switches</th>
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<tbody>
<tr>
<td>FG1</td>
<td>(S1), (S2), (S3), (S4), (S5), (S6)</td>
</tr>
<tr>
<td>FG2</td>
<td>(S1, S2, S3), (S4, S5, S6)</td>
</tr>
<tr>
<td>FG3</td>
<td>(S1, S3), (S2, S4), (S1, S5), (S1, S6)</td>
</tr>
<tr>
<td>FG4</td>
<td>(S2, S5), (S3, S4), (S1, S2), (S1, S3)</td>
</tr>
<tr>
<td>FG5</td>
<td>(S1, S2, S5), (S1, S3, S6), (S2, S4, S5), (S2, S3, S6), (S2, S4, S6)</td>
</tr>
<tr>
<td>FG6</td>
<td>(S1, S2, S4), (S1, S3, S4), (S1, S4, S5), (S1, S3, S5), (S1, S4, S6), (S1, S3, S6)</td>
</tr>
<tr>
<td>FG7</td>
<td>(S1, S2, S4, S5), (S1, S2, S4, S6), (S1, S2, S3, S4), (S1, S2, S3, S5), (S1, S2, S3, S6)</td>
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</table>

(a) Fault group identification algorithm  
(b) Faulty switch identification in FG1

Figure 2. The proposed fault localization algorithm under open-switch fault.

Simulation Results

To verify the effectiveness of the proposed fault detection and localization schemes, the simulation results are presented. The simulations are carried out using the PSIM software. Figure 3 shows the simulation results for the fault detection and localization under different open-switch fault conditions. The open-switch fault occurs at \( t=0.1 \) sec. From the top, each waveform denotes three-phase current responses, the fault detection variables \( F_{\text{flag}} \) and \( F_{\text{status}} \), the fault group \( FG \), and the faulty switches \( F_{\text{sw1}} \), \( F_{\text{sw2}} \), and \( F_{\text{sw3}} \), respectively.

Figure 3(a) and Figure 3(b) show the simulation results when the open-switch faults occur simultaneously in \( S_1 \) and \( S_2 \) of \( FG_4 \) and in \( S_1, S_2, \) and \( S_6 \) of \( FG_5 \), respectively. As shown in these figures, these fault groups develop the same fault signature in view of three-phase current waveforms. Due to this reason, when the fault group is identified as \( FG_4 \) or \( FG_5 \), the free-wheeling mode is forced in the drive system for the purpose of detecting faulty switches in the proposed fault localization algorithm.

By monitoring the positive and negative durations in three-phase current waveforms during the free-wheeling mode, faulty switches can be accurately detected as shown in these figures. While the current waveform in Figure 3(a) has all the positive and negative durations of three-phase currents during the free-wheeling mode, the negative \( c \)-phase current is absent during the free-wheeling mode in current waveform of Figure 3(b) due to the open-switch fault in \( S_6 \).

Figure 3(c) and Figure 3(d) show the simulation results when the open-switch faults occur simultaneously in \( S_1, S_2 \) and \( S_4 \) of \( FG_6 \) and in \( S_1, S_4, \) and \( S_6 \) of \( FG_7 \), respectively. Similarly, by monitoring the positive and negative durations in three-phase current waveforms during the free-wheeling mode, faulty switches can be effectively detected by the proposed scheme.
Summary
To improve the reliability in inverter-fed PMSM drive systems, a simple on-line open-switch fault detection and localization algorithm through current waveform analysis has been presented. The proposed scheme can be easily employed in commercial industrial drive systems without additional equipment. The effectiveness of the proposed scheme has been verified through comparative simulations under various fault conditions.

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References

