Open-switch fault diagnosis in three-level rectifiers based on selective calculation method for instant voltage deviation

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Abstract
This paper presents an open-switch fault detection, and identification method for a neutral-point clamped rectifier system. A new calculation method for phase-to-phase pole voltage deviations is proposed for reducing calculation errors. In this way, the more accurate diagnosis can be achieved. Both single-switch faults, and multiple-switch faults can be identified effectively by using fewer diagnostic variables, which makes the diagnostic method simpler, and more reliable. And all the variables can be simply calculated by signals which are available to the control system of the rectifier, avoiding the use of additional hardware. Moreover, different voltage thresholds are designed for different faulty feature sections to further reduce the diagnostic time. Additionally, a diagnostic result checking method is proposed to avoid the misdiagnosis when considering the effect of outer-switch faults. Finally, experiments are carried out, and the results show the robustness, and effectiveness of the proposed method.

1 | INTRODUCTION

Multilevel converters have more outstanding performance on efficiency and current harmonics than conventional two-level converters, especially for high power appliances. Among three-level converters, the neutral-point-clamped (NPC) converter is the most widely used for its advantages of low collector-emitter voltage stress on switching devices and low harmonic distortion of AC currents [1, 2]. However, NPC converter systems are vulnerable to switching device faults because many switches are used [3, 4]. It is estimated that about 38% of faults in variable-speed AC drives are due to failures in switching devices such as insulated-gate bipolar transistors (IGBTs) [5].

The faults of switching devices can be divided into a short-switch fault and an open-switch fault [6, 7]. A short-switch fault generates abnormal overcurrents which will immediately lead to a breakdown of a converter system. Therefore, the system should be shut down as soon as possible by protection circuits such as circuit breakers and fuses. An open-switch fault does not bring such damage immediately but degrades the performance of the system such as current distortion, ripples of the DC-link voltage and unbalance of the neutral-point voltage. It may lead to more serious secondary faults of the system, if the system remains such abnormal working conditions for a long time.

To detect open-switch faults, fault detection and identification (FDI) methods were proposed. Many studies have been conducted for two-level converters [8, 9]. Most online methods are based on the analysis of currents such as current vectors [10], average currents [11], near-zero currents [12] and line-to-line currents [13], or on the analysis of voltages such as phase pole voltages [14], phase-to-phase pole voltages [15] and gate-voltage behaviour [16]. These methods are called signal-based methods. Another kind of FDI methods are model-based methods which use current or voltage observers to obtain the deviation of the reference signal and the estimated signal [17–19].

As for three-level NPC converters, researches on FDI methods are not as complete as two-level converters, especially for rectifiers. The increasing numbers of switching devices and the different working conditions make the fault diagnosis of NPC converters more complex than two-level converters. Therefore, most FDI methods for two-level converters cannot identify the specific faulty switch when they are applied to NPC converters. And additional methods are needed to complete the diagnosis in this situation. For example, the FDI method based on the
current pattern angle was effectively applied to two-level converters in [10]. However, this method can only identify the faulty phase and the faulty pair of NPC inverters, but not the faulty switch. In [20], the specific switching state was applied to solve this problem, after the fault type was located by the method of the current pattern angle.

The FDI methods for NPC converters can also be divided into current-based methods [20–22], voltage-based methods [23, 24] and model-based methods [25–28]. In [21], a current-based method was proposed for NPC inverters of ac motor drives. The faulty switch was located by analyzing the normalized average currents of each positive and negative half cycle with the current vector method. In [22], the zero-range time of three-phase currents was proposed to be used for detecting open-switch faults in a back-to-back converter with an NPC topology. These current-based methods only require three-phase currents and simple calculations. Therefore, they are easy to implement in NPC converters. However, the diagnostic time is quite long (usually more than 1/3 of a fundamental period). Voltage-based methods are proposed for shorter diagnostic time and stronger independence of the load. These methods are based on the analysis of voltages under normal and faulty conditions. In [23], a voltage-based method was realized by measuring the pole voltage and its duration time. And in [24], the proposed FDI method was also based on the analysis of the pole voltage with the current polarity and the switching state. Both methods have the common disadvantage of voltage-based methods, which require the additional hardware circuit to measure the voltage (resistive voltage dividers in [23] and voltage sensors in [24]). Although the diagnostic time is significantly reduced to several sampling periods, voltage-based methods are not cost-effective.

The model-based methods have the advantage in cost compared with voltage-based methods. They built current or voltage observers to obtain the errors between the reference and the estimated signals. For a single-phase NPC rectifier in the electric railway application, a mixed logical dynamic model was built to estimate the grid current. And the residual between the measured current and the estimated one was used to detect open-circuit faults in [25]. A model-based algorithm was proposed by building a sliding-mode proportional-integral observer to estimate the fault profiles with data processing of the line currents and grid voltages [26].

For three-phase NPC rectifiers, a novel model-based method was proposed by using instant voltage deviations for NPC rectifiers in [27]. The diagnostic variables were calculated by existing signals available in the control system. However, only single-switch faults were considered. The detection of multiple-switch faults was realized in [28]. This method was also based on voltage deviations. And according to the combination of the values of diagnostic variables, the possible faulty combinations were deduced in every instant. And a running table was used to store all unconfirmed fault combinations until new information was available to identify the faulty switches. Therefore, the whole reasoning process is complex, which increases the complexity of the diagnostic algorithm and makes the diagnostic method more unreliable. In the above two methods, rectifier switching states can only be changed at the sampling instant, otherwise large calculation errors are generated, so that the fault diagnosis cannot be achieved. This restriction degrades the performance of the rectifier system under normal working conditions, such as the increase of the current distortion.

To detect open-switch faults in three-level NPC rectifiers, this paper proposes a new calculation method for phase-to-phase pole voltage deviations, which can largely reduce the calculation errors with the normal modulation method. In this way, switching states can be changed at any instant completely determined by the calculation of the control system. Therefore, the diagnosis can be successfully achieved without degrading the system performance. Furthermore, a new set of logical judgment conditions are used to detect both single-switch and multiple-switch faults. In this way, fewer diagnostic variables are used, making the FDI method simpler and more reliable. Additionally, different voltage thresholds are designed for different faulty feature sections to further reduce the diagnostic time. And an FDI result checking method is proposed to avoid the misdiagnosis when considering the effect of outer-switch faults.

This paper is organized as follows. In Section 2, the working conditions of NPC rectifiers are analyzed under open-switch faults. Section 3 introduces the main principle of the proposed FDI method. On this basis, Section 4 propose the new calculation method for diagnostic variables and discusses the selection of thresholds as well as the FDI result checking method. Finally, the proposed FDI method is experimentally verified in Section 5.

2 ANALYSIS OF NPC RECTIFIERS UNDER FAULTY WORKING CONDITIONS

This section analyzes the operation of NPC rectifiers under faulty working conditions compared with normal working conditions. The NPC rectifier topology is shown in Figure 1. There are twelve active switching devices (\(S_{x1}–S_{x4}\), \(x = a, b, c\)) and six clamping diodes (\(D_{a1}–D_{a2}\)). Each switching device includes an anti-parallel diode (\(D_{a1}–D_{a2}\)) respectively. Six switches of the uppermost and the lowermost are named outer switches (\(S_{x1}\) and \(S_{x4}\)) and the other switches between outer switches are named inner switches (\(S_{x2}\) and \(S_{x3}\)) in this paper. \(v_{a}, v_{b}, v_{c}\) are three-phase voltage sources. \(i_{a}, i_{b}, i_{c}\) are AC input currents. \(L\) is the AC side inductance and \(R\) is the AC side resistance. \(C\) is the DC side capacitance, and \(v_{dc}, v_{dc-j1}, v_{dc-j2}\) are capacitor voltages for the upper and the lower respectively. \(R_{L}\) is the DC load and \(v_{dc}\) is the DC-link voltage.

There are three kinds of switching states of each phase, namely \([P],[O]\) and \([N]\), as defined in Table 1.

Under normal working conditions, there are six current paths (1–6) in the rectifier as shown in Figure 2 depending on different combinations of current directions and switching states. And the phase pole voltage always takes the expected value which is consistent with the corresponding switching signals \(s_{x}(x = a, b, c)\) as shown in Table 2 (assuming \(v_{dc-j1} = v_{dc-j2} = v_{dc}/2\). The expected phase pole voltage \(v_{oa}\) can be expressed
FIGURE 1 Topology of three-level NPC rectifier and its control system

TABLE 1 Switching states

| Switching state | $S_{x1}$ | $S_{x2}$ | $S_{x3}$ | $S_{x4}$ |
|-----------------|---------|---------|---------|---------|
| P               | on      | on      | off     | off     |
| O               | off     | on      | on      | off     |
| N               | off     | off     | on      | on      |

FIGURE 2 Current paths under normal working conditions ($\alpha i_x > 0$, $\beta i_x < 0$)

TABLE 2 Switching signals and pole voltages under normal working conditions

| Switching signal $\tau_x$ | Active switches | $v_{xo,E}$ |
|---------------------------|-----------------|------------|
| 1                         | $S_{x1}$ and $S_{x2}$ | $v_{dc}/2$ |
| 0                         | $S_{x2}$ and $S_{x3}$ | 0 |
| -1                        | $S_{x3}$ and $S_{x4}$ | $-v_{dc}/2$ |

FIGURE 3 Changes in current paths under faulty working conditions (a) $S_{x1}$ fault, (b) $S_{x4}$ fault, (c) $S_{x2}$ fault, (d) $S_{x3}$ fault

as:

$$v_{xo,E} = \frac{v_{dc}}{2}.$$  \hspace{1cm} (1)

If an open-switch fault occurs, the current path is different from that of normal working conditions because the switching state does not reach the desired one (consistent with the switching signal). Then undesirable phase pole voltages are produced. So the real phase pole voltage $v_{xo,R}$ is different from the expected phase pole voltage $v_{xo,E}$. This causes the pole voltage deviation, given by:

$$\Delta v_{xo} = v_{xo,E} - v_{xo,R}.$$  \hspace{1cm} (2)

2.1 Outer-switch fault

During the most time, outer switches do not work because most negative currents flow through paths 5 and 6, and most positive currents flow through paths 1 and 2 under normal working conditions. These current paths do not be affected when open-switch faults occur in outer switches. Only a few currents flow through paths 4 and 3 will be changed as shown in Figs. 3(a) and 3(b), which leads to tiny distortion of currents and generates phase pole voltage deviations.

For $S_{x1}$ fault, there is tiny distortion at the beginning of negative half-cycle of $i_x$, and the phase pole voltage changes from the expected value $v_{dc}/2$ to the real value 0, so $\Delta v_{xo} = v_{dc}/2$ as shown in Figure 4(a) (gray areas). For $S_{x4}$ fault, there is tiny distortion at the beginning of positive half-cycle of $i_x$, and the phase pole voltage changes from the expected value $-v_{dc}/2$ to the real value 0, so $\Delta v_{xo} = -v_{dc}/2$ as shown in Figure 4(b) (gray areas).

2.2 Inner-switch fault

The inner-switch faults lead to the expanding duration of current path changes and serious current distortion with two nearly zero sections in a half cycle.
When $i_x = 0$ ($x = a, b, c$), there is no current path. Taking the phase $a$ as an example, for $i_a = 0$, the voltage circuit can be represented as:

$$
\Delta v_a = v_{ao,R} - v_{ao} = v_{ao,R} - \frac{v_{ao,R} + v_{bo,R} + v_{co,R}}{3},
$$

(3)

Then $v_{ao,R}$ can be obtained from (3) as:

$$
v_{ao,R} = \frac{3\Delta v_a + v_{bo,R} + v_{co,R}}{2}.
$$

(4)

Therefore, $v_{ao,R}$ is an uncertain value varying with the $a$-phase voltage source and affected by the other two-phase pole voltages.

When an open-switch fault occurs in inner switches, there are three sections with different faulty features of $\Delta v_{ao}$ in a current half-cycle as shown in Figs. 4(c) and 4(d) (Part B, C, and D). The first one is Part B in which $i_a$ is in the nearly zero sections and $|\Delta v_{ao}|$ is an uncertain value affected by AC voltage sources and other two-phase pole voltages. The second one is Part C in which $|\Delta v_{ao}|$ alternates between $v_{dc}$ and $v_{dc}/2$. The third one is Part D in which $|\Delta v_{ao}|$ alternates between 0 and $v_{dc}/2$. The detailed explanations are as follows.

As shown in Figure 4(c), when $S_{a2}$ fault occurs, there are two nearly zero sections at the beginning and the end of negative half-cycle of $i_a$, called ZS1 and ZS2 respectively in this paper. In these sections (Part B), $s_x = 1$ and $s_x = 0$ alternately, so $v_{ao,E} = v_{dc}/2$ and $v_{ao,F} = 0$ respectively. According to the previous analysis, $v_{ao,R}$ is variable. And in ZS1, $v_{ao,R}$ tends to decrease from 0, whereas in ZS2, $v_{ao,R}$ tends to increase from $-v_{dc}/2$. Therefore, $\Delta v_{ao}$ has the opposite variation tendency. That is, in ZS1, $\Delta v_{ao}$ tends to decrease from 0, whereas in ZS2, $\Delta v_{ao}$ tends to increase from $-v_{dc}/2$ as shown in Figure 4(c). When $i_a < 0$, $v_{ao,R} = -v_{dc}/2$, because the negative current can only flow through $D_{x3}$ and $D_{x4}$ (current paths will change as shown in Figure 3(c)). In Part C, $s_x = 1$ and $s_x = 0$ alternately, so $v_{ao,E} = v_{dc}/2$ and $v_{ao,F} = 0$ respectively. That means, $\Delta v_{ao} = v_{dc}$ and $\Delta v_{ao} = v_{dc}/2$ alternately. And to get rid of nearly zero sections as soon as possible, the control system sends more switching signals of $s_x = 1$ compared with normal working conditions, so $\Delta v_{ao} = v_{dc}$ takes a large part of Part C. In Part D, $s_x = -1$ and $s_x = 0$ alternately, so $v_{ao,E} = -v_{dc}/2$ and $v_{ao,F} = 0$ respectively. That means, $\Delta v_{ao} = 0$ and $\Delta v_{ao} = v_{dc}/2$ alternately.

When $S_{a3}$ fault occurs, the analysis is similar to that of $S_{a2}$ fault. As shown in Figure 4(d), two nearly zero sections are at the beginning (ZS1) and the end (ZS2) of positive half-cycle of $i_a$. In ZS1, $\Delta v_{ao}$ tends to decrease from 0, whereas in ZS2, $\Delta v_{ao}$ tends to increase from $-v_{dc}$. When $i_a > 0$, $v_{ao,R} = v_{dc}/2$, because the positive current can only flow through $D_{x1}$ and $D_{x2}$ (current paths will change as shown in Figure 3(d)). In Part C, $\Delta v_{ao}$ alternates between $v_{dc}$ and $-v_{dc}/2$, whereas in ZS2, $\Delta v_{ao}$ alternates between 0 and $-v_{dc}/2$.

Table 3 summarizes the phase pole voltage deviations under open-switch faults of different switches. The phase pole voltage includes the most direct information on switching states and current paths. Therefore, open-switch faults can be diagnosed through the analysis of the phase pole voltage.

**TABLE 3** Phase pole voltage deviations under faulty working conditions

| Current | Faulty switch | Impossible switching state | $\Delta v_{ao}$ |
|---------|--------------|---------------------------|---------------|
| $i_a \neq 0$ | $S_{a1}$ | P | $v_{dc}/2$ | $v_{dc}/2$ |
|         | $S_{a2}$ | P | $-v_{dc}/2$ | $v_{dc}$ |
|         | $O$ | 0 | $-v_{dc}/2$ | $2v_{dc}$ |
|         | $N$ | $-v_{dc}/2$ | $v_{dc}$ |
| $i_a = 0$ | $S_{a2}$ | P | $v_{dc}/2$ | $<0$ | $>0$ |
|         | O | 0 | $<0$ | $>0$ |
|         | N | $-v_{dc}/2$ | $>0$ | $<0$ |
3 | PROPOSED FDI STRATEGY

As the previous analysis, when an outer-switch fault occurs, the switching state \( P \) at the beginning of the negative current and the switching state \( N \) (called Part A in this paper) at the beginning of the positive current make the voltage deviations non-zero and degrade the system performance, as shown in Figs. 4(a) and 4(b). Therefore, the degree of outer-switch faults affecting the system performance depends on the duration of Part A. Under unity power factor, Part A is small. If Part A is small enough, the outer-switch faults can be ignored [29]. In this situation, it is not necessary to detect outer-switch faults. And no matter under what conditions the rectifier works, the inner-switch faults have a great impact on the rectifier. Therefore, this section focuses on the diagnosis of inner-switch faults when outer-switch faults can be ignored.

3.1 Diagnostic variables

According to the analysis of the previous section, open-switch faults can be detected by the deviation of the expected and real phase pole voltages. To calculate \( \Delta v_{xo} \), the expected phase pole voltage can be obtained by switching signals and the DC-link voltage as (1). But the real phase pole voltage can only be measured by additional hardware which will increase the cost of the diagnosis. Therefore, the deviation of the expected and real phase-to-phase pole voltages is considered as the diagnostic variable instead, because the real phase-to-phase pole voltage can be directly calculated by existing signals, given by:

\[
v_{xy,R} = v_{xo,R} - v_{yo,R} = (\varepsilon_x - R_i - L \frac{di_x}{dt} - v_{wa}) - (\varepsilon_y - R_i - L \frac{di_y}{dt} - v_{wa}) = (\varepsilon_x - \varepsilon_y) - R(i_x - i_y) - L \left( \frac{di_x}{dt} - \frac{di_y}{dt} \right). \tag{5}\]

And the expected phase-to-phase pole voltage is given by:

\[
v_{xy,E} = v_{xo,E} - v_{yo,E}
= \frac{v_x}{2} - \frac{v_y}{2}. \tag{6}\]

The diagnostic variable can be expressed by:

\[
\Delta v_{xy} = v_{xy,E} - v_{xy,R}. \tag{7}\]

Because of the calculation errors caused by sampling errors, dead time and delay time, \( \Delta v_{xy} \neq 0 \) under normal working conditions. Therefore, the voltage threshold \( V_{TH} \) is used to avoid misdiagnosis. And \( f_{xy} \) is used to indicate whether \( \Delta v_{xy} \) exceeds the normal value as:

\[
f_{xy} = \begin{cases} 
1, & \Delta v_{xy} > V_{TH} \\
0, & |\Delta v_{xy}| \leq V_{TH} \\
-1, & \Delta v_{xy} < -V_{TH} \end{cases} \tag{8}\]

where, \( \Delta v_{xy} \in \{\Delta v_{a,b}, \Delta v_{b,c}, \Delta v_{c,a}\} \).

According to the previous analysis, when any open-switch fault occurs, at least one of \( \Delta v_{a,b}, \Delta v_{b,c}, \text{ and } \Delta v_{c,a} \) must exceed the voltage threshold. That is, one of \( f_{a,b}, f_{b,c}, \text{ and } f_{c,a} \) is not 0.

3.2 Single-switch fault

To identify which switch is faulty, more logical conditions are needed. According to the previous analysis, when any single-switch fault occurs, there are two non-zero indicators \( (f_{xy}) \) and they are opposite. For example, a single-switch fault in \( a \) phase makes \( \Delta v_{a,b} = -\Delta v_{a,b} \text{ and } |\Delta v_{a,b}| \leq V_{TH}, S_{a2} \text{ fault makes } \Delta v_{a,b} > V_{TH} \text{ when } i_a < 0 \text{ as shown in Figure 5(a), so it can be concluded that } f_{a,b} = -1 \text{ and } f_{a,c} = 0. \text{ Therefore, a set of logical conditions can be established to identify single-switch faults as shown in Table 4.}

| Faulty switch | \( f_{ab} \) | \( f_{bc} \) | \( f_{ca} \) |
|--------------|------------|------------|------------|
| \( S_{a2} \)  | 1          | 0          | -1         |
| \( S_{a3} \)  | -1         | 0          | 1          |
| \( S_{b2} \)  | -1         | 1          | 0          |
| \( S_{b3} \)  | 1          | -1         | 0          |
| \( S_{c2} \)  | 0          | -1         | 1          |
| \( S_{c3} \)  | 0          | 1          | -1         |
3.3 Multiple-switch fault

Because the possibility of three or more switches fault is very small, this paper only considers the case of double-switch faults. The faulty features of double-switch faults can be regarded as the combination of two single-switch faults. Therefore, the logical conditions of identifying multiple-switch faults are concluded as Table 5 according to Table 4. The detailed explanations are as follows.

Double-switch faults can be classified into three categories: double-switch faults in a phase (Faulty Type 1), upper or lower switch faults in different phases (Faulty Type 2), upper and lower switch faults in different phases (Faulty Type 3).

TABLE 5 Fault identification variables of multiple-switch faults

| Faulty type | Faulty switch | \( f_{ab} \) | \( f_{bc} \) | \( f_{ca} \) |
|-------------|---------------|-------------|-------------|-------------|
| 1 | \( S_2, S_3 \) | ±1 | 0 | ±1 |
| | \( S_2, S_3 \) | ±1 | ±1 | 0 |
| | \( S_2, S_3 \) | 0 | ±1 | ±1 |
| 2 | \( S_2, S_2 \) | ±1 | 1 | −1 |
| | \( S_2, S_2 \) | ±1 | −1 | 1 |
| | \( S_2, S_2 \) | −1 | ±1 | 1 |
| | \( S_2, S_3 \) | 1 | ±1 | −1 |
| | \( S_2, S_2 \) | 1 | −1 | ±1 |
| | \( S_2, S_3 \) | −1 | 1 | ±1 |
| 3 | \( S_2, S_3 \) | 1 | −1 | −1 |
| | \( S_2, S_3 \) | −1 | 1 | 1 |
| | \( S_2, S_3 \) | −1 | 1 | −1 |
| | \( S_2, S_3 \) | 1 | −1 | 1 |
| | \( S_2, S_3 \) | −1 | −1 | 1 |
| | \( S_2, S_3 \) | 1 | 1 | −1 |

**Faulty Type 1:** For this type, one of the indicators (\( f_{ab} \)) is 0, and the other two indicators both have two values of 1 and −1 at different times as shown in Table 5. Taking \( S_2, S_3 \) double-switch fault as an example, it is equivalent to the superposition of faulty features of \( S_2 \) fault and \( S_3 \) fault, and the faulty features do not overlap as shown in Figure 6(a). That is, \( \Delta v_{ab} = -\Delta v_{ab} \) and \( \Delta v_{bc} \leq \Delta v_{bc} \) when \( i_a < 0, \Delta v_{ab} > \Delta v_{bc} \). When \( i_a > 0, \Delta v_{ab} < \Delta v_{bc} \). Therefore, \( f_{ab} = 0, f_{bc} = 0, f_{ca} = 0 \).

**Faulty Type 2:** For this type, one of the indicators (\( f_{ab} \)) has two values of 1 and −1, and the other two indicators are not 0 and are opposite as shown in Table 5. Taking \( S_2, S_2 \) double-switch fault as an example, \( \Delta v_{ab} \) shows the faulty feature of \( S_2 \) fault \( (\Delta v_{ab} > \Delta v_{bc} \text{ when } i_a < 0) \), and \( \Delta v_{bc} \) shows the faulty feature of \( S_2 \) fault \( (\Delta v_{ab} < -\Delta v_{bc} \text{ when } i_a > 0) \) as shown in Figure 6(b). Therefore, \( f_{ab} = 1, f_{bc} = -1 \). There is overlap by 60° in the faulty feature of \( \Delta v_{ab} \) called the overlapping faulty feature section (OFFS) in this paper. In this section, \( S_2 \) fault makes that \( \Delta v_{ab} \) is larger than \( \Delta v_{bc} \) but decreases; \( S_2 \) fault makes that \( \Delta v_{ab} \) is smaller than \( -\Delta v_{bc} \) and decreases. Therefore, \( \Delta v_{ab} \) decreases from positive to negative and \( f_{ab} \) can be one of 1, 0, −1. The values of three indicators (\( f_{ab} \)) may have different combinations which may lead to temporary misidentification in this section. But the identification will be corrected in the end with more diagnostic time (\( f_{ab} = 1 \) and \( f_{ab} = -1 \) are both detected at different times in the end). Therefore, the faulty switch detected firstly in OFFS should not be treated as the final FDI result, but the faulty switch detected last (before leaving OFFS) should be treated as the final FDI result. Besides, considering that the probability of the double-switch fault at the same time in OFFS is very small, there are successive faults of two switches in most cases. Therefore, the overlap of faulty features has little effect on identification.

**Faulty Type 3:** For this type, three indicators (\( f_{ab} \)) are not 0. Two of them have the same value, and the other one has the opposite value as shown in Table 5. Taking \( S_3, S_3 \) double-switch fault as an example, it is equivalent to the superposition of faulty features of \( S_3 \) fault and \( S_2 \) fault as shown in
Figure 6(c). $\Delta v_{dc}$ shows the faulty feature of $S_{d}$ fault ($\Delta v_{dc} > V_{TH}$ when $i_d < 0$), and $\Delta v_{dc}$ shows the faulty feature of $S_{a}$ fault ($\Delta v_{dc} > V_{TH}$ when $i_d > 0$). There is overlap by $120^\circ$ in the faulty features of $\Delta v_{dc}$. But $S_{a}$ fault and $S_{d}$ fault both make that $\Delta v_{dc} < -V_{TH}$, so $\Delta v_{dc}$ is a negative value and decreases significantly. This situation will not lead to misidentification but make the faulty feature more obvious, which is beneficial for the identification. Therefore, $f_{d} = -1$, $f_{c} = 1$, $f_{a} = 1$.

4  PROPOSED CALCULATION METHOD AND THRESHOLD SELECTION

4.1  Calculation method of diagnostic variables

To discretize, the real phase-to-phase pole voltage can be estimated as:

$$v_{3y-R}(k) = (e_y(k) - e_y(k)) - R(i_y(k) - i_y(k))$$

$$- \frac{L}{T_{sp}}[(i_y(k) - i_y(k + 1)) - (i_y(k) - i_y(k + 1)))] \quad (9)$$

where $T_{sp}$ is the sampling period and $k$ is the $k$th sampling point.

And the expected phase-to-phase pole voltage can be estimated as:

$$v_{3y-E}(k) = v_{3a-E}(k) - v_{3c-E}(k). \quad (10)$$

Because the values of $v_{3a-E}$ and $v_{3c-E}$ are not exactly the same especially under faulty working conditions and they can also be measured by existing sensors without additional hardware, $v_{3a-E}$ is redefined for more accurate calculation as:

$$v_{3a-E}(k) = \begin{cases} 
  v_{3a-E}(k) & i_y(k) = 1 \\
  0 & i_y(k) = 0 \\
  -v_{3a-E}(k) & i_y(k) = -1 
\end{cases}. \quad (11)$$

Therefore, the deviation of the expected and real phase-to-phase pole voltages can be written as:

$$\Delta v_{3y}(k) = v_{3y-E}(k) - v_{3y-R}(k). \quad (12)$$

According to (9), the appropriateness of sampling is a key factor to ensure the accuracy of the calculation. Moreover, the change in the switching signals of each phase will cause the trends of three-phase currents to change as shown in Figure 7. If the change in switching signals happens between two sampling points ($k$ and $k - 1$), the calculated current rate-of-change is different from the actual one as shown in Figure 7 ($L_i d_i(k)/dt \neq L_i i_y(k) - i_y(k - 1)/T_{sp}$), and the calculation of $\Delta v_{3y}(k)$ according to $k$ and $k - 1$ will have two results: the first result is the inaccurate calculation of $L_i i_y(k) - i_y(k - 1)/T_{sp}$ and $L_i i_y(k) - i_y(k - 1)/T_{sp}$ leading to the calculation error as shown in Figure 7 (red points and areas); the second result is the inaccurate calculation but the calculation error is offset by the error of $L_i i_y(k) - i_y(k - 1)/T_{sp}$ and the error of $L_i i_y(k) - i_y(k - 1)/T_{sp}$ as shown in Figure 7 (orange points and areas). That is, the calculation error may be generated and will be relatively large, because the sampling period is short. The calculation error may lead to misdiagnosis, so it should be reduced. It is easily indicated that if there are no changes in switching signals between two sampling points, the calculation is accurate as shown in Figure 7 (blue points and areas). Therefore, a selective calculation method is proposed. Two successive sampling points $k$ and $k - 1$ between which there are no changes in switching signals are selected as the calculation points. That is, if there are no changes in switching signals between $k$ and $k - 1$, $v_{3y-R}(k)$ is calculated by (9) and $\Delta v_{3y}(k)$ is calculated by (12). Otherwise, no calculation is carried out and $\Delta v_{3y}(k)$ is treated as 0.

It should be pointed out that using the seven-stage SVPWM method, the switching state changes six times (two times per phase) in a switching period. If the sampling frequency is at least six times the switching frequency, six calculation points will generate the calculation error in a switching period in the worst case (each phase switching signal changes at non-sampling points). If the worst case is considered, the sampling frequency is better to be greater than six times the switching frequency.

4.2  Threshold selection

As mentioned above, the voltage threshold is used as a comparator to determine if $|\Delta v_{dc}(k)|$ is large enough to be considered as an error. $V_{TH}$ is defined according to the DC-link voltage. The smaller the value of $V_{TH}$, the faster the diagnosis, but at the same time, the lower the reliability of the diagnosis.
To make the proposed FDI method applicable to different faulty sections, the selection of voltage thresholds should take zero and non-zero sections of currents into consideration. In the nearly zero sections of currents, $\Delta v_{xy}(k)$ is not a fixed value that can vary from $-v_{d6}$ to $v_{d6}$ under faulty working conditions. Whereas in the non-zero sections of currents, the value of $\Delta v_{xy}(k)$ can be one of $0, \pm v_{d6}/2, \pm v_{d6}$ (without considering the overlap of faulty features). Therefore, $V_{TH}$ can be set as $v_{d6}/2$ for high accuracy of the diagnosis. However, if the fault starts at the nearly zero sections of currents, the diagnosis may need more time by using the same threshold, because $\Delta v_{xy}(k)$ is an increasing/decreasing value beginning from 0 in this section. Two voltage thresholds are defined to solve this problem. $V_{TH1}$ which is a smaller value is used when $i_x = 0$ or $i_y = 0$. $V_{TH2}$ which is a larger value is used when $i_x \neq 0$ and $i_y \neq 0$.

Therefore, two voltage thresholds are defined as:

$$V_{TH1,2}(k) = \left\{ \begin{array}{ll} V_{TH1}, & I_x(k) = 0 \\ V_{TH2}, & I_y(k) = 1 \end{array} \right.$$  \hspace{1cm} (13)

where, $I_x(k) = 0$ means that $i_x(k)$ or $i_y(k)$ is in the nearly zero sections, and $I_y(k) = 1$ means that $i_x(k)$ and $i_y(k)$ are all in the non-zero sections.

According to the faulty features in nearly zero and non-zero sections of currents as shown in Figures 5 and 6, the value around $v_{d6}/2$ is appropriate for $V_{TH2}$, and the value around $v_{d6}$ is appropriate for $V_{TH1}$. Since the real value of $v_{d6}$ is variable, especially in the case of open-switch faults (the DC-link voltage will fluctuate greatly), the voltage thresholds is updated based on the measured $v_{d6}$. And the DC-link voltage signal is measured by existing sensors without additional hardware. Therefore, Equation (13) can be rewritten as:

$$V_{TH1,2}(k) = \left\{ \begin{array}{ll} v_{d6}(k) - V, & I_x(k) = 0 \\ v_{d6}(k) - V, & I_y(k) = 1 \end{array} \right.$$  \hspace{1cm} (14)

where, $V$ is a relatively small constant (can be chosen as 2% of the DC-link voltage) to ensure the effectiveness of the diagnosis in the section of $\Delta v_{xy}(k) = v_{d6}/2(k)$ considering that calculation errors cannot be avoided.

Considering that currents contain ripples and noise components, $I_{TH}$ is set to determine whether $i_x(k)$ and $i_y(k)$ are in the nearly zero sections, which can be chosen as 5% of the current amplitude. Therefore, $I_x(k)$ can be expressed as:

$$I_x(k) = \begin{cases} 0, & |i_x(k)| \leq I_{TH1} \text{ or } |i_y(k)| \leq I_{TH2} \\ 1, & |i_x(k)| > I_{TH1} \text{ and } |i_y(k)| > I_{TH2} \end{cases}.$$  \hspace{1cm} (15)

It is necessary to point out that under normal working conditions, the current can also be treated as in the nearly zero sections when it goes from positive/negative to negative/positive, and the voltage threshold will also change. However, this situation will not affect the diagnosis.

The time threshold is also employed to compensate for delay time and dead time in rectifiers. The sliding window algorithm is adopted to count the sampling points when $|\Delta v_{xy}(k)| > V_{TH1,2}(k)$. If $|\Delta v_{xy}(k)| > V_{TH1,2}(k)$ for a long enough time (\(\geq T_{TH}\)) in a sliding window, then it may be concluded that there is an open-switch fault. Considering that $\Delta v_{xy}(k)$ is calculated by two sampling points, $T_{TH}$ can be set as two sampling periods (including three sampling points) to ensure the accuracy of the diagnosis.

### 4.3 Outer-switch fault effect

The previous analysis focuses on the diagnosis of inner-switch faults when outer-switch faults can be ignored. However, the duration of Part A depends on the modulation index and current amplitude [29], and it can be extended as shown in Figure 8. By greatly increasing the current and decreasing the modulation index, although the duration of Part A increases slightly, the influence of outer-switch faults on the system is still small compared with inner-switch faults. Therefore, inner-switch faults are the main concern. However, in this situation, the outer-switch fault may be detected but be mistaken as an inner-switch fault by the proposed FDI method. There are two situations: $S_{x1}$ fault may be mistaken as $S_{x2}$ fault, and $S_{x4}$ fault may be mistaken as $S_{x3}$ fault. Therefore, under the premise of ensuring the diagnostic speed of inner-switch faults, a special diagnostic strategy is discussed to avoid the misdiagnosis.

Outer-switch faults make the maximum value of $\Delta v_{xy}$ to be $v_{d6}/2$, while inner-switch faults make the maximum value of $\Delta v_{xy}$ to be $v_{d6}$. Since the influence of outer-switch faults on the system is reflected at the beginning of positive or negative half-cycle currents, if it is an outer-switch fault, three $\Delta v_{xy}$ will not exceed $v_{d6}/2$ within 1/8 of a current cycle after the fault is detected, otherwise the FDI result is correct.

Therefore, a new voltage threshold $V_{check}$ is designed to check the diagnostic results. Considering the calculation error is inevitable, $V_{check}$ is chosen as $v_{d6}(k)/2 + V$. If an outer-switch fault is detected at $k_{11}$ for every sampling point $k_i$ within 1/8 of a current cycle $T$ after $k_{11}$, three $\Delta v_{xy}$ are compared with $V_{check}(k_i)$ as:

$$M_{xy}(k_i) = \begin{cases} 0, & |\Delta v_{xy}(k_i)| < V_{check}(k_i) \\ 1, & \text{else} \end{cases}.$$  \hspace{1cm} (16)
Then the checking signal is defined as:

$$F_{\text{check}} = \begin{cases} 0, & \sum_{i=1}^{n} M_{xy}(k_i) = 0 \\ 1, & \text{else} \end{cases}$$

(17)

where $n = T/(8T_{sp})$.

If $F_{\text{check}} = 0$, the FDI result is wrong and can be corrected as shown in Table 6. Once $\Delta v_{xy}(k_i) \geq V_{\text{check}}(k_i)$ which means that $F_{\text{check}} = 1$, the FDI result is correct. In this way, outer-switch faults can be detected when their influence cannot be ignored. However, more diagnostic time is required.

To conclude the proposed FDI scheme, the block diagram is shown in Figure 9.

5 | EXPERIMENTAL RESULTS

In this section, experiments are carried out to verify the effectiveness and the reliability of the proposed FDI method.

5.1 | Experiment setup

The experimental platform includes an NPC rectifier prototype, a digital signal processor (DSP) TMS320F28335, and a host computer as shown in Figure 10. The DSP receives voltage and current signals from the main circuit through the sensors and outputs switching signals to control the switches. Also, the DSP realizes the proposed FDI method and saves the diagnostic signals. After the experiments, the diagnostic signals are exported to the host computer and replotted by MATLAB.

The rectifier system adopts a double closed-loop controller with the space vector pulse-width modulation (SVPWM) and the neutral-point voltage balancing control strategy as shown in Figure 1. The neutral-point voltage balancing control is used to make the upper and lower capacitor voltages as stable as possible even under faulty working conditions of the rectifier [30]. Therefore, $v_{dc_H}$ and $v_{dc_L}$ used in the diagnosis are the existing signals available to the neutral-point voltage balancing control.

The main parameters of the system are given in Table 7. According to these parameters, the thresholds used in the experiments are set as $I_{TH} = 0.1A$ (about 5% of the current amplitude), $V = 6V$ (about 2% of $V_{dc}$), $T_{TH} = 2T_{sp} = 50\mu s$ (two sampling intervals including three sampling points). And the voltage thresholds are updated in real-time with the DC-link voltage. 

FIGURE 9 | Block diagram of the proposed FDI scheme

FIGURE 10 | Experimental setup
TABLE 7 Main parameters of the rectifier system

| Parameters                  | Symbols | Value    |
|-----------------------------|---------|----------|
| Grid voltage                | \( e_a, e_b, e_c \) | 110V (rms) |
| Grid frequency              | \( f \)      | 50Hz     |
| Switching frequency         | \( f_s \)        | 5kHz     |
| Sampling period             | \( T_s \)       | 25\( \mu \)s |
| AC side inductance          | \( L \)         | 5mH      |
| DC side capacitance         | \( C \)         | 940\( \mu \)F |
| Load                        | \( R_L \)      | 200\( \Omega \) |
| Given DC-link voltage       | \( V_{dc} \)   | 300V     |

FIGURE 11 Experimental results of robustness analysis under transient changes (a) The DC-link voltage, (b) Three-phase currents, (c) \( \Delta v_{ab} \) and \( V_{TH_{ab}} \), (d) \( \Delta v_{bc} \) and \( V_{TH_{bc}} \), (e) \( \Delta v_{ca} \) and \( V_{TH_{ca}} \)

5.2 Robustness analysis

Figure 11 shows the robustness experiment of the proposed FDI method by changing the given DC-link voltage \( V_{dc} \) and the load power \( P, V_{dc} \) is set to increase from 300V to 350V at 1.01s; \( P \) is set to increase from 0.6kW to 1.2kW at 1.04s and decrease to 0.12kW at 1.06s. Those transient changes in the system make the DC-link voltage and AC currents fluctuate violently. Although the calculation errors cannot be eliminated, the values of diagnostic variables (\( \Delta v_{ab}, \Delta v_{bc}, \Delta v_{ca} \)) are always within the voltage thresholds (grey lines) with the appropriate setting of voltage thresholds. And no false alarm occurs. Besides, the voltage thresholds change according to the change of the DC-link voltage as shown in Figs. 11(d)–11(f) (grey lines).

FIGURE 12 Experimental results of \( S_{a2} \) fault at 1.01s and \( S_{a3} \) fault at 1.045s (a) Three-phase currents, (b)\( \Delta v_{ab} \) and \( V_{TH_{ab}} \), (c)\( \Delta v_{bc} \) and \( V_{TH_{bc}} \), (d)\( \Delta v_{ca} \) and \( V_{TH_{ca}} \), (e) Intermediate result, (f) FDI result

This means that there are no misdiagnosis due to the transient change of the DC-link voltage.

In conclusion, the transient changes of the system will not cause the misdiagnosis, which means the robustness of the proposed FDI method is verified.

5.3 Effectiveness analysis

Figs. 12–15 show the diagnostic results of single-switch faults and multiple-switch faults to prove the validity and the rapidity of the proposed FDI method. The open-switch fault is simulated by setting the switching signal of the faulty switch as 0 in this section. The intermediate result signals \( f_{SP,p} \) and \( f_{SP,n} \) represent \( f_{S_{ij}} \) in Tables 4 and 5, and indicate that \( \Delta v_{ij} \) is larger than \( V_{TH_{ij}} \) for \( T_{TH} \) and \( \Delta v_{ij} \) is smaller than \( -V_{TH_{ij}} \) for \( T_{TH} \) respectively.

Single-Switch Fault: As shown in Figure 12, \( S_{a2} \) open-switch fault occurs at 1.01s making the negative half-cycle of \( i_a \) distorted greatly with two nearly zero sections. In the first zero section, \( \Delta v_{ab} (\Delta v_{bc}) \) gradually increases (decreases) and exceeds the voltage threshold. Then \( S_{a2} \) fault is detected by giving the fault signal \( f_{S_{a2}} = 1 \) with the diagnostic time of 1.2 ms. Whereas in Figure 13, an open-switch fault is applied to \( S_{a2} \) at 1.005s, but...
detected at the same instant as Figure 12. This is because that $S_{a2}$ does not work when $i_a > 0$ (the positive current does not flow through $S_{a2}$), which means the effect of $S_{a2}$ fault on the system begins from $i_a$ leaving the positive half-cycle. In this situation, the diagnostic time should be calculated from the beginning of the half cycle of currents when the faulty switch works. Therefore, the actual diagnostic time of $S_{a2}$ fault in Figure 13 is 1.2 ms which is the same as Figure 12. Besides, the setting of the smaller voltage threshold $V_{TH1}$ can significantly accelerate the diagnosis when $S_{a2}$ fault begins from the nearly zero section of $i_a$ as shown in Figure 12 (the grey area at 1.01s).

**Faulty Type 1:** Figure 12 shows the diagnostic result of Faulty Type 1. First, a single open-switch fault is applied to $S_{a2}$ at 1.01s. Then $S_{a3}$ is set to a fault at 1.045s as a secondary fault. As the previous analysis of Faulty Type 1, the faulty feature does not overlap. $S_{a3}$ fault can be detected quickly with the diagnostic time of 0.375 ms which is the same as Figure 12. Besides, the setting of the smaller voltage threshold $V_{TH1}$ can significantly accelerate the diagnosis when $S_{a2}$ fault begins from the nearly zero section of $i_a$. However, $S_{a3}$ fault begins from the non-zero section of $i_a$. Therefore, the proposed FDI method is applicable to open-switch faults that occur in both the zero section or non-zero section of the current.

**Faulty Type 2:** Figure 13 shows the diagnostic result of Faulty Type 2. First, a single open-switch fault is applied to $S_{a2}$ at 1.005s. Then $S_{a3}$ is set to a fault at 1.036s (at the beginning of OFFS, which is one of the worst situations) as a secondary fault. As the previous analysis of Faulty Type 2, the faulty feature overlaps by 60° (maximum) as shown in Figure 13(b). This situation makes the temporary misdiagnosis as shown in Figure 13(f) (red line representing $S_{a3}$ fault). Because when $\Delta v_{bc} > V_{TH1}$ is detected, $\Delta v_{ab} < -V_{TH1}$ is undetected as shown in Figure 13(e). But with more diagnostic time, $S_{a2}$ fault is detected before leaving OFFS. Therefore, the FDI result can be corrected quickly by setting the faulty signal of $S_{a3}$ to 0. $S_{b2}$ fault can be detected with the diagnostic time of 1.13 ms. Besides, if the secondary switch fault occurs in other sections instead of in OFFS, the temporary misdiagnosis will not be generated.

**Faulty Type 3:** Figure 14 shows the diagnostic result of Faulty Type 3. First, a single open-switch fault is applied to $S_{a3}$ at 1.02s. Then $S_{b2}$ is set to a fault at 1.045s as a secondary fault. As the previous analysis of Faulty Type 3, the faulty feature overlaps by 120° (maximum) as shown in Figure 14(b). But $S_{a3}$ fault and $S_{b2}$ fault both make that $\Delta v_{ab} < -V_{TH1}$, so the faulty feature is more obvious, which accelerates the diagnosis. $S_{a3}$ fault can be detected quickly with the diagnostic time of 0.325 ms.

**Outer-Switch Fault Effect:** Figure 15 shows the diagnostic result when considering the outer-switch fault effect. By changing experimental parameters, outer-switch faults can be detected. $S_{a1}$ open-switch fault occurs at 1.01 s and are misdiagnosed...
Table 8 Comparison of the proposed FDI method with previous methods

| Reference | System       | Types of fault                          | Diagnostic time | Additional hardware |
|-----------|--------------|-----------------------------------------|-----------------|---------------------|
| Proposed method | NPC rectifier | Single- and multiple-switch fault       | < 50 sampling periods | No need            |
| [24] NPC inverter | Single- and multiple-switch fault, clamp-diode fault | < 20 sampling periods | Need               |
| [27] NPC rectifier | Single-switch fault | < 80 sampling periods | No need            |

Figure 15 Experimental results of \( S_{a1} \) fault at 1.01s and \( S_{a2} \) fault at 1.03s
(a) Three-phase currents, \( \Delta V_{\text{ref},ab} \), \( V_{\text{check},ab} \), \( \Delta V_{\text{ref},bc} \), \( V_{\text{check},bc} \), (b) \( \Delta V_{\text{ref},ca} \), \( V_{\text{check},ca} \), (c) Intermediate result, (d) FDI result and checking result as \( S_{a2} \) fault after 0.45 ms. However, the checking signal \( F_{\text{check}} \) remains 0 after 1/8 of a current cycle when the fault is detected. Therefore, the FDI result is corrected as \( S_{a1} \) fault at about 1.013s. At the same time, the intermediate result signals \( f_{\text{check},p} \) and \( f_{\text{check},n} \) are reset for the following diagnosis as shown in Figure 15(e). Then \( S_{a2} \) open-switch fault occurs at 1.03s and are detected after 0.275 ms. And then \( F_{\text{check}} = 1 \) confirms that this FDI result is correct.

In conclusion, the accuracy of the proposed FDI method is verified. Besides, \( R \) in Figure 1 is the equivalent resistance of the inductance. It is a small value and when calculating the diagnostic variables, \( R \) is ignored in (9). And \( L \) is treated as a fixed value in (9). However, in the experiments, the actual value of \( L \) is variable because the inductance may vary with temperature and conducted current. Therefore, the parameters used in the calculation do not match the actual parameters in the experiments. However, as shown in the above results, the parameter mismatch will not affect the proposed FDI method.

5.4 Comparison with previous methods

The performance of the proposed FDI method is compared with previous methods as shown in Table 8, such as the application system, the diagnostic capability, the diagnostic time, and the cost. The diagnostic time refers to the detection of single-switch faults. The proposed FDI method can detect both single-switch faults and multiple-switch faults in NPC rectifiers with fast speed. And it is cost-effective without using an additional hardware circuit.

6 CONCLUSION

This paper introduces an FDI method based on instant phase-to-phase pole voltage deviations and a selective calculation method for open-switch faults of NPC rectifiers. The deviations between the expected phase-to-phase pole voltage and the real phase-to-phase pole voltage are utilized as the diagnosis variables. All these variables are calculated by the signals existing in the double closed-loop controller, avoiding the use of additional hardware. The real phase-to-phase pole voltage is calculated when there are no changes in switching states between two sampling points, which is called a selected calculation method. In this way, the large calculation errors can be reduced to ensure the accuracy of the diagnosis. Finally, the robustness and the effectiveness of the proposed FDI method are analyzed by experiments. The experimental results show that the proposed method has strong robustness on transient changes, and can identify both single-switch faults and multiple-switch faults effectively with fast diagnostic speed. The diagnostic time can be within 1.2 ms for single-switch faults. For multiple-switch faults, the diagnostic time is related to complicated factors such as the faulty type, the faulty sequence of two switches and the faulty feature section in which the fault occurs.

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