Open-circuit fault diagnosis method for three-level neutral point clamped inverter based on instantaneous frequency of phase current

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Abstract
Because the three-level neutral point clamped (NPC) inverter has the advantages of a large output capacity and high output voltage, it is widely used in wind energy and solar energy generation. Unfortunately, the three-level NPC inverter often suffers from open-circuit faults, which leads to system security problems and great economic losses. To guarantee the secure operation of the three-level NPC inverter, an open-circuit fault diagnosis method for a three-level NPC inverter based on the instantaneous frequency (IF) of the phase current is proposed here. First, different open-circuit fault signals of the NPC inverter are analysed. Then, the IF of the phase current is used to obtain the fault diagnosis variables. Simultaneously, the Hilbert transform (HT) is used to estimate the IF of the phase current, which carries the information of open-circuit faults. Meanwhile, the average value of the normalised current is provided to locate faulty switches. Finally, by combining the diagnostic variables with the identification threshold, the detection and localisation of open-circuit faults in the NPC three-level inverter are determined. Compared to other fault diagnosis methods, the proposed method is more stable and makes it easier to diagnose open-circuit faults. The correctness and robustness of the method are verified by simulation results.

1 | INTRODUCTION

Compared with two-level inverters, NPC three-level inverters have the advantages of large output capacity, high output voltage, and low current harmonics [1,2]. Therefore, it has been widely used in renewable energy generation fields, such as wind and solar energy generation. The NPC three-level inverter is responsible for the central actuator of the power generation control in renewable energy generation systems. However, the NPC three-level inverter uses large power switch devices and operates under high temperature, high current, and high voltage for a long period. The power switch device of the three-level NPC inverter has a higher fault rate and lower reliability [3]. To ensure secure and reliable operation of the NPC three-level inverter, fault diagnosis of the power switch device should be timely and accurate.

Generally, power switch faults can be divided into open-circuit and short-circuit faults. The current of a short-circuit fault is large, and the time of fault occurrence is short. Usually, short-circuit faults are turned into open-circuit faults by adding a fast fuse to the circuit of the power switch device [4]. Open-circuit faults usually do not cause a sharp increase in current, so this phenomenon is not easily detected. However, other power switches will overcurrent if a power switch is exposed to an open-circuit fault for a long time. This leads to secondary faults and the collapse of the three-level NPC inverter system [5]. Among the open-circuit faults of the three-level NPC inverter, the single power switch open-circuit fault is the most common in real applications; therefore, it is particularly important and useful to diagnose a single-power-switch open-circuit fault.

For these reasons, open-circuit fault diagnosis methods for power switches have received wide attention in recent years and...
can be divided into current-based and voltage-based methods [6–8]. However, these voltage-based methods require additional voltage sensors, which are not easy to implement because they increase the cost and complexity. Nevertheless, these algorithms depend on the model’s precision and require the parameters of the machine. This causes many difficulties in real applications.

Open-circuit fault diagnosis of power switches can also be achieved by using the most widely adopted method: the current-based method. In [9], Park’s vector approach was proposed to diagnose the voltage source inverter for the first time. However, this method always needs to be combined with pattern recognition algorithms, which is different to integrate into the drive controller. Based on this approach, the average current Park’s vector approach was proposed in [10]. This method determines the range of the phase angle of the average current Park’s vector to detect the switch fault. This has a high dependency on the load and is sensitive to transients, which results in low diagnostic effectiveness and false results.

In [11], the phase angle slope of the current Park’s vector was provided to diagnose an open-circuit fault. An open-circuit fault diagnosis method based on normalised phase currents was introduced in [12]. In [13], the main component analysis and neural network were used to diagnose microgrid inverter faults under load change conditions. In [14], the signal symmetry reconstitution preprocessing method was proposed. Based on multistate data processing and subsection fluctuation analysis, a multiple open-circuit fault diagnosis method for inverters under load vibration conditions was proposed in [15]. A method based on the multilevel feature moving average ratio method was proposed in [16]. However, most of these methods are typically used for two-level inverter fault diagnosis, and there are few studies on the fault diagnosis of three-level NPC inverters.

For the open-circuit fault diagnosis of a three-level NPC inverter, in [17], a novel fault diagnosis approach based on knowledge-driven and data-driven data was presented for open-circuit faults in insulated-gate bipolar transistors of the NPC inverter. This proposed method can locate open-circuit faults of IGBTs in the NPC inverter under different loads. However, the core disadvantage of the data-driven method is that it requires magnanimous data. In addition, applying this method to actual engineering accurately and efficiently is a difficult issue. In [18], a new approach for open-circuit fault detection and location of the NPC three-level inverter was proposed. Compared with the traditional fault diagnosis method, the speed of fault location using the proposed algorithm is quick and accurate. However, the process of establishing a fault tree is cumbersome, and using this method to achieve fault diagnosis usually depends on the experience and ability of the analyst. In [19], a novel multilayer neural network was proposed to diagnose all possible open-circuit faults. Furthermore, principal component analysis was utilised to reduce the input size of the neural network. The proposed method had the advantages of good classification performance and high reliability. However, the proposed method combined the principal component with a multilayer neural network. This requires large amounts of data, and the accuracy of the result is low when the data are insufficient.

In [20], a bank of sliding-mode proportional-integral observers was suggested to estimate the fault profiles under an additive model. In [21], fault-tolerant control schemes for a neutral-point-clamped three-level inverter-fed permanent magnet synchronous motor drive with double stator windings were proposed, and both open-phase faults and open-switch faults were considered. However, these methods require intricate modelling, which adds complexity to the system.

Based on the above analysis, to overcome these shortcomings and ensure the security of the NPC system, a new open-fault diagnosis method based on the instantaneous frequency of the phase current for the NPC inverter is proposed here. First, different open-circuit fault signals of the NPC inverter are analysed. Then, the IF of the phase current is estimated using a Hilbert transform, and the IF of the current is used to obtain the fault diagnosis variables. Meanwhile, the average value of the normalised current is provided to locate faulty switches. Finally, by combining the diagnostic variables with the identification threshold, the open-circuit faults for the three-level NPC inverter are detected and localised.

The remainder is organized as follows: Section 2 analyses the current signal of a three-level NPC inverter. In Section 3, a new open-circuit fault diagnosis method is proposed. In Section 4, the simulation results are presented to test the effectiveness of this method. Finally, the conclusion is provided in Section 5.

## 2 | ANALYSIS OF CURRENT SIGNALS FOR THREE-LEVEL NPC INVERTER SYSTEM

The typical topological structure of a three-level NPC inverter system is shown in Figure 1. The structure is mainly composed of a DC source, LC filter, loads, grid, and inverter. The inverter consists of two capacitances (C1 and C2) and three arms (A, B, and C). Each arm includes four power switches, four free-wheel diodes, and two clamping diodes. The current signals ($I_a$, $I_b$, $I_c$) of the three-phase inverter can be divided into three types: normal state, single open-switch fault, and double open-switch fault. Because the failure rate of a single power switch is much higher than that of double power switches, a single-power-switch open-circuit fault will be analysed here. Owing to the
symmetrical topology of the inverter, open faults of different switches in the same state will have similar fault signal features.

The three-phase current signal of a normal-state three-level NPC inverter is shown in Figure 2. As Figure 2 shows, the fluctuation of the three-phase current waveform is smooth when the inverter is in a normal state.

Figure 3 shows the three-phase current signal of Va1 when an open-switch fault occurs. As shown in Figure 3, when the Va1 open-switch fault occurs at 0.1 s, the positive amplitude of \( I_a \) decreases partly. Meanwhile, the corresponding currents \( I_b \) and \( I_c \) also change: the bottom half of the signal has a slight decrease, and the amplitude and waveform are changed. In addition, the waveform of the \( I_a \) distortion is the largest, and the amplitudes of \( I_b \) and \( I_c \) change slightly. According to the symmetry of the topology for the inverter switch, Vb1 and Vc1 have similar fault signal features.

Figure 4 shows the three-phase current signal of Va2 when an open-circuit fault occurs. As shown in Figure 4, when the Va2 open-switch fault occurs at 0.1 s, the upper half of \( I_a \) approaches zero. According to Figures 3 and 4, the distortions of \( I_a \) are different, the positive amplitude of \( I_a \) decreases partly when Va1 experiences an open-circuit fault, and the positive amplitude of \( I_a \) decreases to zero when Va2 undergoes an open-circuit fault. Thus, the fault characteristic is inapparent when Va1 has an open-circuit fault. Simultaneously, the corresponding amplitudes of \( I_b \) and \( I_c \) decreased slightly. Vb2 and Vc2 had similar fault signal features owing to the symmetry of the topology.

Figure 5 shows the three-phase current signal of Vb3 when an open-circuit fault occurs. As shown in Figure 5, when the Vb3 open-switch fault occurs at 0.1 s, the bottom half of \( I_b \) disappears. Simultaneously, the corresponding amplitudes of \( I_a \) and \( I_c \) change slightly. Furthermore, the waveform of \( I_b \) distortion is the largest, and the amplitudes of \( I_a \) and \( I_c \) change slightly. According to the symmetry of the topology of the inverter switch, Va3 and Vc3 have similar fault signal features.
Figure 6 shows the three-phase current signal of Vb4 when an open-switch fault occurs. As shown in Figure 6, when a Vb4 open-switch fault occurs at 0.1 s, the negative amplitude of \( I_b \) decreases partly. According to Figures 5 and 6, the distortions of \( I_a \) are different, the negative amplitude of \( I_a \) decreases partly when Va4 experiences an open-circuit fault, and the bottom half of \( I_a \) disappears when Va3 undergoes an open-circuit fault. Thus, the fault characteristic is obvious when Va3 has an open-circuit fault. Meanwhile, the corresponding currents of \( I_a \) and \( I_b \) are different when Va1 or Va2 have an open-circuit fault. As shown in Figure 6, when an open-circuit fault occurs, the negative amplitude of \( I_a \) decreases partly when Va1 experiences an open-circuit fault, and the amplitudes of \( I_a \) and \( I_c \) change slightly in both cases.

When comparing the signals, it can be easily seen that the distortions of \( I_b \) are different when Va1 or Va2 have an open-circuit fault, the positive amplitude of \( I_b \) decreases partly when Va1 experiences an open-circuit fault, and the positive amplitude of \( I_b \) decreases to zero in another situation. Thus, the fault characteristic is inapparent when Va1 has an open-circuit fault. Meanwhile, the amplitudes of \( I_a \) and \( I_b \) change slightly in both cases. According to the symmetry of the topology for the inverter switch, Va4 and Vc4 have similar fault signal features.

3 | PROPOSED FAULT DIAGNOSIS ALGORITHM

A new method based on instantaneous frequency is proposed here for diagnosing faults. A block diagram of the proposed fault diagnosis method is illustrated in Figure 7. This approach first detects an abnormal inverter operation by evaluating which phase is faulty. Then, according to the fault phase, additional tests are performed to localise the specific faulty device. The proposed fault diagnosis approach only uses three-phase currents, which can be easily obtained from the main control system. Hence, the proposed method avoids using extra sensors and avoids increasing system complexity and costs.

3.1 Fault-phase detection method

Based on the above analysis, a new open-fault detection method based on the instantaneous frequency of the phase current for an NPC is proposed here. Typically, the traditional instantaneous frequency (IF) \( f(t) \) of a real signal \( x(t) \) is defined based on the well-known Hilbert transform (HT) as follows:

\[
f(t) = \text{HT}(x(t)) = \frac{1}{2\pi} \text{d arctan}(y(t)/x(t))
\]

where \( y(t) \) is the HT of \( x(t) \).

\[
y(t) = \text{HT}(x(t)) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau
\]

Based on the IF of the signals, the proposed method is constructed in three steps:

Step 1: Obtain the named three-phase output current \( I_j(t) \). \( j \) represents phase \( j \), and \( j = a, b, c \). Using \( f_j(t) \) and HT (Equations 1 and 2), obtain IF \( f_j(t) \) as follows:

\[
y_j(t) = \text{HT}(I_j(t)) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{I_j(\tau)}{t-\tau} d\tau
\]

\( y_j(t) \) represents the HT of \( I_j(t) \),

\[
f_j(t) = \text{HT}(y_j(t)/I_j(t))
\]

Step 2: Define theoretical instantaneous \( f = 50 \text{ Hz} \). The absolute value of IF residuals \( |err_j(t)| \) can be defined by the following expression:

\[
|err_j(t)| = \left| \frac{f_j(t)}{f} - 1 \right|
\]

Step 3: The average value of \( |err_j(t)| \) defined as \( \mu_j \) can be formulated as follows:

\[
\mu_j = \frac{1}{N} \sum_{k=1}^{N} |err_{jk}|
\]

where \( b \) represents the number of current samples during a fundamental period, and \( b = [1, 2, \ldots, N] \). It is
easy to see that if the arm $j$ has a single-power-switch open-circuit fault, then $\mu_j > 0$. Therefore, a constant $\mu_1$ is defined to compare with $\mu_j$ to judge whether the arm $j$ is in fault.

Fault localisation method

These diagnostic variables, which were calculated by HT, only carry information about the faulty phases. However, these diagnostic variables are incapable of locating the faulty power switches. Combining these variables with average values $v_j$ can identify the faulty power switch, and $v_j$ can be calculated as follows:

$$ v_j = \frac{1}{N} \sum_{h=1}^{N} \left( \frac{I_{jh}}{I_{jh\text{max}}} \right) $$\text{(7)}

where $I_{jh}$ represents the samples of $I_j(t)$, $I_{jh\text{max}}$ represents the maximum value of $I_{jh}$. Apparently, for the open fault in the upper arm $j$, the corresponding $v_j$ will be less than zero. For the open faults in the lower arm, the corresponding $v_j$ will be greater than zero.

Based on the above analysis, by combining $\mu_j$ and $v_j$, three threshold values can be used to achieve open-circuit fault detection: $\mu_1 = 0.18$, $v_1 = 0.2$, and $v_2 = 0.3$. The values of $\mu_1$, $v_1$, and $v_2$ were empirically selected by performing fault detection in a wide range of operating conditions, which was a tradeoff between fault diagnosis sensitivity and robustness against false alarms. In addition, these thresholds are selected after the phase current has been normalised, so these thresholds are also applicable to other inverter systems that have been normalised.

First, the fault phase is judged by comparing the values of $\mu_j$ and $\mu_1$. Then, the faulty switch is located by comparing the values of $v_j$ and $v_1$, $v_2$. The final judgment can be made only when the two conditions meet the threshold requirements. The fault diagnosis criteria can be formulated as follows:

$$ \mu_j > 0.18 $$

$$ v_j < -0.2 $$

$$ v_j > 0.18 $$

shown in Figure 1, the simulation model includes a three-phase inverter, 400-V DC sources, LC filter, bus, and load of 1000 W. The frequency of the three-phase output current is 50 Hz. Furthermore, the simulation results are composed of four parts: three-phase output current signal, average value of absolute value of IF residual $\mu_j$, average values of the normalised current $v_j$, and the fault location. Moreover, in this simulation, six inverter faults are considered: Va1, Va2, Va3, Va4, Vb2, and Vc4.

Figure 8 presents the simulation results of the Va1 fault diagnosis of the three-level NPC inverter. The gate signal is removed from Va1 at $t = 0.1$ s. It can be seen that three phase currents of the three-level NPC inverter are sinusoidal under a normal state, and $\mu_{a} = \mu_{b} = \mu_{c} = 0$ before $t = 0.1$ s. The positive amplitude of $I_a$ suddenly decreases partly at $t = 0.1$ s and the value of $\mu_a$ immediately increases and approaches 0.18. At $t = 0.125$ s, $\mu_a = 0.18$, and $\mu_a > 0.18$ after this moment mean that phase a is detected as faulty after $t = 0.125$ s. Meanwhile, $\mu_a < 0.18$ and $\mu_a < 0.18$ indicate that phase b and phase c are in a normal state. Furthermore, $-0.3 \leq v_j \leq -0.2$ means that the faulty power switch is located at $t = 0.117$ s, and the faulty power switch is Va1 (refer to Table 1). Evidently, $0.025 > 0.017$, and it is easily known that the time of fault detection and location is 0.025 s. According to the symmetry of the topology for the inverter switch, Vb1 and Vc1 have similar fault diagnosis features.
TABLE 1 Fault diagnosis criteria

| Faulty power switch | Judgement condition |
|---------------------|---------------------|
| None                | $\mu_j = 0, r_j = 0$ |
| Vj1                 | $\mu_j \geq \mu_1$ and $r_j \leq r_1$ |
| Vj2                 | $\mu_j \geq \mu_1$ and $r_j \leq r_1$ |
| Vj3                 | $\mu_j \geq \mu_1$ and $r_j \geq r_2$ |
| Vj4                 | $\mu_j \geq \mu_1$ and $r_1 \leq r_2$ |

FIGURE 9 Simulation results of Va2 fault diagnosis of three-level NPC inverter

It can be easily seen from the simulation results of the Va2 fault diagnosis of the three-level NPC inverter in Figure 9 that the power switch Va2 operates at $t = 0.1$ s. Similar to Figure 9, the three-phase currents of the three-level NPC inverter are sinusoidal under a normal state, and $\mu_j = 0$ ($j = a, b, c$) before $t = 0.1$ s. The upper half of the waveform of $i_a$ suddenly approaches zero at $t = 0.1$ s, and the value of $\mu_j$ immediately increases and approaches 0.5. At $t = 0.125$ s, $\mu_a = 0.18$, and $\mu_b \geq 0.18$ after this moment mean that phase $a$ is detected as faulty after $t = 0.115$ s. Meanwhile, $\mu_a < 0.18$ and $\mu_b < 0.18$ indicate that present phases $b$ and $c$ are in the normal state. Furthermore, $r_j \leq -0.3$ means that the faulty power switch is located at $t = 0.103$ s, and the faulty power switch is Vb2 (refer to Table 1). The time of fault diagnosis was 0.017 s. It is clear that Vc2 has similar fault diagnosis features when comparing Figure 9 with Figure 10.

The simulation results of the Va3 fault diagnosis of the three-level NPC inverter are shown in Figure 11. The gate signal is removed from Va3 at $t = 0.09$ s. The three-phase currents of the three-level NPC inverter are sinusoidal under a normal state, and $\mu_j = 0$ ($j = a, b, c$) before $t = 0.09$ s. The upper half of the waveform of phase b suddenly approaches zero at $t = 0.086$ s, and the value of $\mu_j$ immediately increases and approaches 0.5. At $t = 0.101$ s, $\mu_b = 0.18$, and $\mu_j \geq 0.18$ after this moment mean that phase a is detected as faulty after $t = 0.101$ s. Meanwhile, $\mu_b < 0.18$ and $\mu_a < 0.18$ indicate that phase $a$ and phase $c$ are in a normal state. Furthermore, $r_j \leq -0.3$ means that the faulty power switch is located at $t = 0.107$ s and the faulty power switch is...
Va3 (refer to Table 1). It is easily known that the time difference between the fault occurrence and fault location is 0.017 s. According to the symmetry of the topology for the inverter switch, Vb3 and Vc3 have similar fault diagnosis features.

Figure 12 presents the simulation results of the Va4 fault diagnosis of the three-level NPC inverter. The gate signal is removed from Va4 at $t = 0.09$ s. It can be observed that three phase currents of the three-level NPC inverter are sinusoidal under a normal state, and $\mu_i = 0$ before $t = 0.09$ s. The negative amplitude of $I_c$ suddenly decreases partly at $t = 0.09$ s, and the value of $\mu_i$ immediately increases and approaches 0.18. At $t = 0.115$ s, $\mu_i = 0.18$, and $\mu_c \geq 0.18$ after this moment indicate that phase a is detected as faulty at $t = 0.115$ s. Meanwhile, $\mu_i < 0.18$ and $\mu_c < 0.18$ indicate that phase b and phase c are in a normal state. Furthermore, $0.2 \leq v_j \leq 0.3$ means the fault power switch is located at $t = 0.107$ s and the faulty power switch is Va4 (refer to Table 1). The time of fault detection and location is 0.025 s.

Figure 13 shows the simulation results of the Vc4 fault diagnosis of the three-level NPC inverter. The gate signal is removed from Vc4 at $t = 0.1$ s. Three-phase currents of the three-level NPC inverter are sinusoidal under a normal state, and $\mu_i = 0$ before $t = 0.1$ s. The negative amplitude of $I_c$ suddenly decreases partly at $t = 0.1$ s, and the value of $\mu_i$ immediately increases and approaches 0.18. At $t = 0.125$ s, $\mu_i = 0.18$, and $\mu_c \geq 0.18$ after this moment indicate that phase c is detected as faulty at $t = 0.125$ s. Meanwhile, $\mu_i < 0.18$ and $\mu_c < 0.18$ indicate that phase a and phase b are in a normal state. Furthermore, $0.2 \leq v_j \leq 0.3$ means that the fault power switch is located at $t = 0.117$ s and the faulty power switch is Vc4 (refer to Table 1). The time of fault detection and location was 0.025 s. It is apparent that Vb4 has similar fault diagnosis features when comparing Figure 12 with Figure 13.

Through the open-circuit fault-diagnostic simulation results of the three-level NPC converter, it can be observed that the time of fault detection and fault location is 0.017 s or 0.025 s, respectively. When a Vj1 or Vj4 fault occurs, the time of fault detection is 0.025 s. However, the time of fault detection is 0.015 s when a Vj2 or Vj3 fault occurs. The time of fault detection and location includes the inherent time influence of the detection algorithm and location algorithm. Furthermore, the open-circuit fault time of the switch will also affect it. For example, a switch fault occurs in the next half-wave period of the current after the switch operates. In this case, the time delay of up to 50% of the current cycle will increase.

To further demonstrate the performance of the proposed fault diagnosis method, summaries and comparisons were made with some existing algorithms in Table 2 under a 50-Hz three phase condition. In [17], a fault diagnosis approach based on being knowledge driven and data driven was presented for the open-circuit faults of the NPC inverter. This method requires a large amount of data. In [18], an approach for open-circuit fault detection and location included in the detection and location algorithm. In [19], a multilayer neural network was proposed to diagnose all possible open-circuit faults. However, the multilayer neural network requires a large amount of data. A bank of sliding-mode proportional-integral observers was suggested to estimate the fault profiles under an additive model in [20]. However, this method needs to construct an intricate model for the NPC

**TABLE 2** Summaries and comparisons

| Research | Data used | Model dependence | Diagnosis time | Complexity |
|----------|----------|------------------|----------------|------------|
| [17]     | Large    | Low              | >20 ms         | High       |
| [18]     | Large    | Low              | —              | High       |
| [19]     | Large    | Low              | —              | High       |
| [20]     | Small    | High             | 16.5 ms        | Normal     |
| Proposed | Small    | Low              | 15 ms          | Low        |
system. The method proposed here uses only three-phase currents as its inputs, which can be directly obtained from the main control system. Furthermore, this method does not require large amounts of data or an intricate model. Above all, this method can avoid using additional sensors and decreasing the diagnosis complexity and costs; it is relatively simple compared with existing diagnosis algorithms.

5 | CONCLUSION

By utilising the change properties of three-phase current, a new open-circuit fault diagnosis method for a three-level NPC inverter based on the instantaneous frequency of the phase current was proposed here. In the proposed method, different open-circuit fault signals of the NPC inverter were first analysed. Then, the IF of the phase current was estimated by a Hilbert transform, and the IF of the current was used to obtain the fault diagnosis variables. Meanwhile, the average value of the normalised current was provided to locate faulty switches. Finally, by combining the diagnostic variables with the identification threshold, open-circuit faults for the NPC three-level inverter were detected and localised.

Because the proposed method only requires a small number of mathematical operations, it is simpler compared with the existing diagnosis algorithm. Consequently, integrating the diagnosis method into the main control system is effortless.

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