An open-circuit fault diagnosis method for a submodule in a high-frequency-link modular multilevel DC transformer

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Abstract
A high-frequency-link modular multilevel DC/DC transformer (H-M2DCT) is used to interconnect DC bus bars of different voltage levels, and its safe and stable operation helps ensure the reliability of the entire DC grid. However, there is little research on the open-circuit failures of H-M2DCT submodules. Based on an electrical characteristics analysis of the open-circuit fault of the H-M2DCT submodule, this paper proposes a submodule open-circuit fault detection method based on wavelet analysis. By performing wavelet analysis on each arm current, the coefficient is used as a criterion to detect whether a submodule open-circuit fault has occurred on the arm; in terms of fault location, an over-voltage protection method based on the submodule capacitor voltage is adopted. The proposed method requires neither the establishment of a complicated mathematical model nor the installation of additional sensors; thus, rapid detection and localisation of the fault submodule are achieved while reducing computational demand. In addition, the validity and effectiveness of the proposed method can be verified on the MATLAB/Simulink simulation platform.

1 INTRODUCTION

With the development of energy power generation methods and the implementation of various energy conservation and emissions reduction policies, DC power sources and DC loads, such as solar power stations, storage batteries and electric vehicle charging stations, have been widely used in practical applications. Compared with AC grids, DC grids can realise the efficient long-distance transmission of high-voltage (HV) and high-power electric energy, and they are compatible with various DC equipment and save power supply corridors [1,2]. Therefore, the DC grid is a promising technology for the construction of future grids. At present, HVDC transmission technology is widely used worldwide [3–5]. However, during operation, different DC grids use different voltage levels for various reasons, resulting in the need for voltage-level conversion in the DC grid. Furthermore, the traditional DC converter topology cannot meet the voltage and capacity requirements; thus, the interconnection of DC grids remains a challenge.

H-M2DCT, which combines a modular multilevel converter (MMC) and a dual active bridge (DAB), is a recently proposed DC transformer topology. By adopting a high-frequency transformer, it can reduce equipment volume while meeting the voltage and capacity requirements [6,7]. Many theoretical analyses and experimental verifications on the working principle, modulation mode and control strategy of this equipment have been carried out [8–10]. As the key equipment for realising electrical energy conversion and electrical isolation in the DC grid, whether an H-M2DCT can operate safely and stably directly affects the reliability of the DC grid. However, in current public studies, only reference [11] reported the DC fault characteristics of a three-phase modular multilevel DCT with an AC frequency of 500 Hz. To date, despite being the most common fault in an H-M2DCT, there has been little research on submodule open-circuit faults. Exploring an efficient submodule open-circuit fault diagnosis method will effectively improve the reliability of this equipment and ensure the stable operation of DC grids.

Since the structure of an H-M2DCT is similar to that of an MMC, it is helpful to learn from the MMC submodule open-circuit fault diagnosis method. There are two types of MMC submodule open-circuit fault diagnosis methods: (1) those based on parameter design and (2) those based on artificial intelligence. The former constructs a prediction function to achieve fault diagnosis by comparing the predicted value with...
the actual value. A synovial observer was used to predict the current of the submodule in reference [12], and Deng et al. [13] proposed a method that obtained the predicted value of the arm current through the state observer. However, this method constructs complex mathematical functions, and it is difficult to meet the submodule fault diagnosis requirements of an H-M2DCT because the number of submodules is large and the working frequency is high. Reference [14] showed a submodule open-circuit fault detection method based on a support vector machine. This method can achieve efficient MMC open-circuit fault diagnosis without establishing a mathematical model, but it failed to accurately locate the fault submodule. A clustering algorithm for detecting submodule failures was proposed in reference [15], but its feasibility remains to be verified. In addition, reference [16] proposed adding additional sensors to the submodules for detecting faults. This method leads to design difficulties in the submodules, and sensor failures will lead to protection misjudgements.

Considering the structural similarities and differences between an H-M2DCT and an MMC, and based on an open-circuit fault characteristics analysis of an H-M2DCT submodule, this paper proposes an open-circuit fault detection method based on wavelet analysis, and the method based on the submodule capacitor voltage amplitude method is used to locate the fault submodule. The proposed method can quickly locate single or multiple submodule open-circuit faults at different locations without designing complex mathematical functions and installing additional sensors, making it easy to implement in a microprocessor.

Here, the operating principle of an H-M2DCT is first introduced; next, the application of wavelet analysis in H-M2DCT submodule open-circuit fault detection with fault analysis is discussed; then, the fault location method based on the submodule capacitor voltage amplitude method is presented; and finally, the correctness and effectiveness of the proposed method are verified on the MATLAB/Simulink platform.

2 OPERATING PRINCIPLE OF H-M2DCT

The circuit configuration of a single-phase H-M2DCT is shown in Figure 1. The AC side adopts a high-frequency transformer to realise voltage matching, which can effectively improve the power density of the equipment, thereby reducing the volume of the equipment. Both sides of the high-frequency transformer are full bridge groups M1 and M2, which both have an H-bridge structure. Each bridge arm in the group contains N submodules and a bridge arm inductance Ls, and the submodules are connected in series. Because the voltage levels of the primary and secondary sides are not equal, the numbers of submodules in M1 and M2 are not necessarily equal; the submodule adopts a half bridge structure composed of two insulated gate bipolar transistors (IGBTs) in series with perpendicular diodes and a parallel capacitor. The topology is designed by modularisation, and it can meet the voltage and capacity demands and realise the DC–AC–DC voltage transformation using the full bridge groups on both sides.

H-M2DCT uses a single-phase-shifting (SPS) control method to adjust the magnetic flux density of the high-frequency transformer by using the difference in the phase angle, thereby controlling the output voltage [9]. To reduce the harmonic content of the intermediate communication link and facilitate the extraction of fault features, nearest level approximation modulation (NLM) was adopted.

H-M2DCT adopts phase-shifting control. In the full bridge group, the number of submodules placed into operation for each arm in the group is adjusted by the control strategy and modulation method to control the output AC voltages \( v_1 \) and \( v_2 \). Phase-shift control is used between the full bridge groups on both sides. By controlling the magnitude and direction of the phase-shift angle between the drive signals of the full bridge groups M1 and M2, the direction and magnitude of the transmitted power at both ends of the H-M2DCT are controlled [9]. The output AC voltage of the whole bridge group on both sides of the H-M2DCT is determined by the voltage of each bridge arm in the group, while the arm voltage is determined by the number of submodules placed into operation on the arm. The relationship between the arm voltage and the output voltage of the submodules is shown in Equation (1):

\[
\begin{align*}
    v_{ij} &= \sum_{s} f_{sm,ij,k} \quad (1) \\
    f_{sm,ij,k} &= S \cdot v_{c,ij,k}
\end{align*}
\]

where \( v_{ij} \) represents the sum of the output voltages of the submodules of arm \( j \) of full bridge group \( i \); \( f_{sm,ij,k} \) and \( k \) represent

 FIGURE 1 Topological structure of high-frequency-link modular multilevel DC/DC transformer (H-M2DCT)
the output voltages of the $k$ submodule of arm $j$ and $r_c$, $i$ and $k$ are the capacitor voltages of submodule $k$ of arm $j$.

Because H-M2DCT has strict symmetry, a mathematical model is established by taking the M1 group as an example. The electrical quantity in the M2 group can be converted by the transformer ratio. The current and voltage directions of the nodes of the M1 group are shown in Figure 2, where $V_{DC1}$ is the DC voltage of the M1 group; $I_{DC1}$ is the DC current of the M2 group; $i_j$ ($i = 1, 2, j = 1, 2$) is the $j$th arm current of the $i$th group; $i_{ij}$ ($i = 1, 2, j = 1, 2$) is the output AC voltage of the $i$th group; and $i_{ij}$ ($i = 1, 2$) is the output AC current of the $i$th group.

The Kirchhoff voltage equation is established for loop 1 and loop 2 in Figure 2, and it can be written as follows:

$$
\begin{align*}
R_{i11} + R_{i12} + r_{i1} + r_{i2} + L_s \frac{d i_{11}}{dt} + L_s \frac{d i_{12}}{dt} &= V_{DC1} \\
R_{i13} + R_{i14} + r_{i1} + r_{i2} + L_s \frac{d i_{13}}{dt} + L_s \frac{d i_{14}}{dt} &= V_{DC1} \\
L_s \frac{d i_{13}}{dt} - L_s \frac{d i_{14}}{dt} &= v_{i1} \\
L_s \frac{d i_{12}}{dt} - L_s \frac{d i_{14}}{dt} &= v_{i1}
\end{align*}
$$

(3)

According to Kirchoff’s current law, Equation (4) can be obtained:

$$
\begin{align*}
i_{i1} - i_{i2} &= i_{i4} - i_{i3} = i_j \\
i_{i1} + i_{i3} &= i_{i2} + i_{i4} = I_{DC1}
\end{align*}
$$

(4)

According to the operating principle of H-M2DCT, there is a relationship between the arms in the full bridge group, as shown in Equation (5):

$$
\begin{align*}
v_{i1} &= L_s \frac{d i_{i4}}{dt} \\
v_{i2} &= L_s \frac{d i_{i4}}{dt} \\
i_{i1} &= i_{i4} \\
i_{i2} &= i_{i3}
\end{align*}
$$

(5)

Ignoring the circulating current between the arms, the expressions of the DC voltage and AC voltage of the M1 group can be obtained according to Equations (3)–(5), such as Equation (6):

$$
\begin{align*}
\frac{d i_{i1}}{dt} &= \frac{d i_{i4}}{dt} = \frac{V_{DC1} - v_{i1} - v_{i2} - v_{i3}}{2L_s} \\
\frac{d i_{i2}}{dt} &= \frac{d i_{i3}}{dt} = \frac{V_{DC1} + v_{i1} - v_{i2} - v_{i3}}{2L_s}
\end{align*}
$$

(6)

The electric quantity $A$ in the M2 group is converted to the M1 group by the transformer ratio to obtain the electric quantity $A'$, which is obtained according to Equation (7):

$$
\begin{align*}
\frac{d i_{i1}'}{dt} &= -R \frac{v_{i2}'}{2} - L_s \frac{d v_{i2}'}{dt} + v_{i2}' - v_{i2}' \\
\frac{d i_{i2}'}{dt} &= -\frac{R}{2} i_{i3}' - \frac{L_s}{2} \frac{d i_{i3}'}{dt} + v_{i2}' + v_{i2}'
\end{align*}
$$

(7)

During normal operation of H-M2DCT, the DC currents $I_{DC1}$ and $I_{DC2}$ on both sides of the system are constant, and the resistance on the arm is negligible; thus, Equations (6) and (7) are often expressed as the following:

$$
\begin{align*}
\frac{d i_{i1}'}{dt} &= \frac{v_{i1} - v_{i2} - v_{i3}}{2L_s} \\
\frac{d i_{i2}'}{dt} &= \frac{v_{i2} + v_{i2}'}{2L_s}
\end{align*}
$$

(8)

$$
\begin{align*}
\frac{d i_{i1}'}{dt} &= \frac{v_{i1} - v_{i2} - v_{i3}}{2L_s} \\
\frac{d i_{i2}'}{dt} &= \frac{v_{i2} + v_{i2}'}{2L_s}
\end{align*}
$$

(9)

Equations (8) and (9) are general time-domain mathematical models of H-M2DCT, and they are applicable to all modulation modes under phase-shift control. Using triangle wave modulation, two-level modulation, sine wave modulation and other modulation methods will affect only the amplitude of the output AC voltage of the whole bridge group but not the other electrical quantities.

3 | DETECTION METHOD FOR AN OPEN-CIRCUIT FAULT OF A SUBMODULE IN H-M2DCT

3.1 | Current characteristics during a submodule open-circuit fault

According to Equations (3) and (4), the expressions of the arm currents in the group on both sides of H-M2DCT can be derived as the following:

$$
\begin{align*}
\frac{d i_{i1}}{dt} &= \frac{d i_{i4}}{dt} = \frac{V_{DC1} - v_{i1} - v_{i2} - v_{i3}}{2L_s} \\
\frac{d i_{i2}}{dt} &= \frac{d i_{i3}}{dt} = \frac{V_{DC1} + v_{i1} - v_{i2} - v_{i3}}{2L_s}
\end{align*}
$$

(10)
When an open-circuit fault occurs in a submodule, the capacitor voltage of the submodule will deviate from the normal value, and the numbers of submodules in which the upper and lower arms are placed into the system are asymmetric, resulting in different degrees of distortion in the currents of the arms in the system (as shown in Figure 3). Therefore, arm current distortion is an important characteristic of the open-circuit failure of the submodule. By detecting the distortion of the arm current, it can be determined whether there is a faulty submodule in the system. The method based on wavelet analysis determines the differences between the characteristics of the current changes of each arm for detecting the arm where the fault submodule is located.

3.2 Open-circuit fault detection method based on wavelet analysis

3.2.1 The basic principles of wavelet analysis

Wavelet analysis is an excellent signal time-frequency analysis tool. Compared with the traditional Fourier transform, the wavelet transform can represent the local features of the signal in both the time and frequency domains and quickly detect a sudden change in the signal. Compared with the short-time Fourier transform, the wavelet transform can be used for multiresolution analysis to analyse signals at multiple scales so that various details in the signal can be fully displayed. The fault detection method based on wavelet analysis is essentially a fault detection technology based on data analysis; it uses the resolution of the wavelet transform to analyse the details in the signal to find the difference between the faulty arm current and the non-faulty arm current. Wavelet analysis can be used to obtain the detail coefficient as a criterion and to locate the arm where the faulty submodule is located.

In wavelet analysis, the mother-wavelet \( \psi(t) \) is first stretched and translated to obtain a wavelet function family \( \psi_{j,k}(t) \). Then, a scale function family \( \phi_{j,k}(t) \) orthogonal to \( \psi_{j,k}(t) \) is obtained. Finally, the signal \( x(t) \) is expanded into a linear superposition of \( \psi_{j,k}(t) \) and \( \phi_{j,k}(t) \) by using multiresolution analysis, in which the expansion of discrete wavelet analysis of signals can be expressed as

\[
x(t) = \sum_{k} c_{j_0,k} \phi_{j_0,k}(t) + \sum_{j=j_0}^{n} \sum_{k} d_{j,k} \psi_{j,k}(t),
\]

where \( j_0 \) is the initial degree; \( n \) is the number of transform layers; \( c_{j,k} \) is the scale coefficient, also known as the approximation coefficient, which reflects the low-frequency component of the signal; and \( d_{j,k} \) is the detail coefficient, which reflects the high-frequency component of the signal. Equation (8) can effectively express different components of signal \( x(t) \). The process of solving \( c_{j,k} \) and \( d_{j,k} \) from signal \( x(t) \) is called the discrete wavelet transform (DWT).

3.2.2 Optimal wavelet function for submodule open-circuit fault detection

Wavelet analysis essentially uses coefficients to show the similarity between the components of the original signal in each frequency band and the wavelet functions of different scales. In practical applications, the selection of the wavelet function is not unique. Different wavelet functions can obtain different results when analysing the same engineering problem. Therefore, the optimal wavelet function is difficult in terms of the engineering application of wavelet analysis. When the arm current is used as the fault detection parameter, the selected wavelet should have good localisation in both the time and frequency domains and...
be sensitive to the singularity of the signal; it can extract the instantaneous, singular and mutation components of the arm current.

Daubechies (dbN) series wavelet functions have no explicit mathematical expressions. The N in dbN represents the vanishing moment of the wavelet function. The larger the vanishing moment, the larger the support length and the stronger the corresponding wavelet function oscillation (as shown in Figure 4). This series of wavelet functions is a class of mother wavelets with orthogonality, tight time–frequency support and high normality. They meet the requirements of the proposed fault detection method for mother wavelets. Figure 4 shows a shape diagram of a dbN wavelet function and a fault current signal with different vanishing moments.

For fault detection, the optimal wavelet function is a wavelet with a high degree of matching with the electrical characteristics of the fault. The Pearson correlation coefficient shown in Equation (13) is often used to measure the degree of correlation between two variables, and its value ranges between $-1$ and $1$. Therefore, by comparing the Pearson correlation coefficients between different wavelet functions and fault signals, the best matching wavelet function can be selected for fault detection:

$$
\tau = \frac{\sum (X - \bar{X})(W - \bar{W})}{\sqrt{\sum (X - \bar{X})^2 \sum (W - \bar{W})^2}}. 
$$

(13)

In Equation (13), $X$ is the fault signal; $W$ is the wavelet function; and $\bar{X}$ and $\bar{W}$ are the averages of the fault signal and the wavelet function, respectively. The fault signal $X$ is shown in Figure 4, and the corresponding wavelet function $W$ is the Daubechies wavelet function.

When calculating the Pearson correlation coefficient, the fault current signal is normalised so that its amplitude is equal to the amplitude of the wavelet function, and then Equation (11) is used for calculation. The results obtained are shown in Figure 5. By comparing the correlation coefficients, we know that the db6 wavelet is the optimal wavelet function. It should be pointed out that the size of the Pearson correlation coefficient is closely related to the system parameters of the H-M2DCT. When the system parameters change, the correlation coefficient between the wavelet function and the fault current signal needs to be recalculated to select the optimal wavelet function and achieve fault detection.

3.2.3 | Failure detection process

Take the submodule open-circuit fault happened on arm 11 as an example, the fault detection method proposed is shown in Figure 6.

The arm current signals in the full bridge group are collected on both sides, and wavelet analysis is performed on each arm current. When the detail coefficient of an arm current is $|d_{x,j,k}^{x}| > |\eta_x d_{x,j,k}^{n_x}|$, $x = 1, 2$, and five consecutive sampling periods appear ten times, it can be determined that the arm is where the faulty submodule is located. Because the parameters of the full bridge groups M1 and M2 on both sides of the H-M2DCT are not exactly the same, their values are different. $d_{x,j,k}^{n_1}$ and $d_{x,j,k}^{n_2}$ are the maximum values of detail coefficients of M1 and M2 under normal operation; $d_{x,j,k}^{1}$ and $d_{x,j,k}^{2}$ are the detail coefficients obtained by real-time wavelet analysis; and the thresholds $\eta_1 d_{x,j,k}^{n_1}$ and $\eta_2 d_{x,j,k}^{n_2}$, generally with $\eta = 2 - 5$, are the empirical values obtained through simulation verification.

4 | FAULT LOCATION METHOD BASED ON SUBMODULE CAPACITOR VOLTAGE

In an H-M2DCT, since the direction of the arm current will change very quickly when the AC frequency is above 1000 Hz, it will be difficult to locate the faulty submodule position according to existing methods [15,18]. The submodule of H-M2DCT adopts a half bridge structure, and its submodule open-circuit fault is divided into two types: an upper open-circuit fault and a lower open-circuit fault. Under normal operation, the submodule has two working modes, and its working principle is shown in Table 1.

Table 1 shows that, when H-M2DCT is under normal operation, the submodule capacitor has three states: charging,
discharging and not charging. The charging time of the capacitor is the same as that of discharging, and the voltage of the submodule capacitor fluctuates up and down within a certain range. An H-M2DCT model built on the MATLAB/Simulink simulation platform is used to further analyse the open-circuit fault characteristics of the submodule. Submodule 1 on arm 11 is set to have an open-circuit fault at 2 s, and the capacitor voltage of the fault submodule is shown in Figure 7.

Combining the contents of Table 1 and Figure 7, it can be seen that, when the upper IGBT $S_1$ of the submodule has an open-circuit fault, that is, when $S_1$ is always equal to 0, regardless of the current direction, the capacitor of the submodule has only two states, i.e. charging and bypassing, and there is no discharging process. Therefore, the capacitor voltage of the faulty submodule continues to increase during the fault. When an open-circuit fault occurs in the lower IGBT $S_2$, that is, $S_2$ is always equal to 0, although the submodule capacitor has three working states, the capacitor is in a charging state during the current direction $A \rightarrow B$. Even if there is a discharging process in the current direction $B \rightarrow A$, the capacitor voltage of the faulty submodule is still higher than the capacitor voltage of the non-faulty submodule. In an H-M2DCT, because the AC frequency

### TABLE 1  Operating principle of the submodule

| Schematic diagram | $S_1$ | $S_2$ | Current direction | Capacitance state | Operating mode |
|-------------------|------|------|-------------------|-------------------|----------------|
| ![Schematic diagram](image) | 0 | 0 | $A \rightarrow B$ | Charge | Input |
| ![Schematic diagram](image) | 0 | 1 | $A \rightarrow B$ | Not charge | Input |
| ![Schematic diagram](image) | 0 | 0 | $B \rightarrow A$ | Discharge | Bypass |
| ![Schematic diagram](image) | 0 | 0 | $B \rightarrow A$ | Not charge | Bypass |
is very high, the switching frequency of the submodule is also higher than the switching frequency of the submodule in the MMC. When an open-circuit fault occurs in the submodule, the capacitor module voltage rises quickly, and the fault characteristics are obvious. The submodule capacitor voltage amplitude can be used as a criterion to quickly locate the faulty submodule.

The fault location method proposed is shown in Figure 8. When the capacitor voltage of a submodule \( U^x_{sm} > k_1 U^1_{sm} \) continues to exceed \( T_q \), it can be determined that the submodule has an open-circuit fault. \( U^1_{sm} \) and \( U^2_{sm} \) are the average values of the submodule voltages of the M1 group and the M2 group during normal operation; \( U^s_{sm} \) and \( U^n_{sm} \) are the real-time sampling values of the capacitance voltages of one of the M1 group and the M2 group; and the fault location thresholds are \( k_1 U^1_{sm} \) and \( k_2 U^2_{sm} \), respectively (\( k_{sm} = 1.1 \) to 1.4); the fault location delay is \( T_q \).

When using this method to locate the fault, the sampling frequency of the capacitor voltage of the submodule is only 2–5 times the switching frequency, which can ensure the integrity of the capacitor voltage information of the submodule and greatly reduce the sampling workload. When calculating the average value of capacitor voltage under normal operation, capacitor voltage information in 10 switching cycles is selected arbitrarily. After calculating the average value of a single switching cycle through multipoint sampling, the average value of 10 switching cycles is added up and divided by 10 to obtain the average value of capacitor voltage under normal operation. Because fault location starts after fault detection is completed, the capacitor voltage of the fault submodule has risen; thus, the delay time \( T_q \) should be as short as possible, i.e. 2–5 times that of the switching cycle.

### TABLE 2  
High-frequency-link modular multilevel DC/DC transformer (H-M2DCT) model parameters

|                         | Primary side | Secondary side |
|-------------------------|--------------|----------------|
| DC voltage              | 10 kV        | 20 kV          |
| Number of single arm submodules | 10 | 20 |
| Submodule capacitor    | 2.5 mF       | 2.5 mF         |
| Arm inductance          | 1 mH         | 3 mF           |
| AC transformer frequency| 1000 Hz      |                |

### 5 | SIMULATION

To verify the effectiveness of the proposed method, an H-M2DCT model with a ratio of 1:2 and a capacity of 1 MW was built on the MATLAB/Simulink platform, which can set up the open-circuit fault in the submodule. The topological structure is shown in Figure 1. SPS control is used to control the magnetic flux density of the transformer by controlling the phase angle difference to control the output voltage of the H-M2DCT. The modulation method adopts the NLM, which effectively solves the voltage equalisation problem of the submodule. The specific model parameters are shown in Table 2.

#### 5.1 | Normal operation

Figure 9 shows the node waveforms of H-M2DCT during normal operation. Figure 9(a) and (b) shows the DC voltage and current on the primary and secondary sides; Figure 9(c) shows the AC voltage and current of the primary and secondary sides of the high-frequency transformer; Figure 9(d) and (e) shows the arm current of the M1 and M2 groups; and Figure 9(f) and (g) shows the partial submodule capacitor voltage of the M1 and M2 groups.

It can be seen from the simulation results that the H-M2DCT model can realise DC voltage conversion with a ratio of 1:2. The average capacitance voltage of the submodule is 1000 V, which is much lower than what the submodule can achieve in the current production process; the number of submodules in the full bridge group is similar to that of the actual project. Thus, the obtained data have practical significance.

#### 5.2 | Submodule open-circuit fault diagnosis

Taking the submodule open-circuit faults that occurred on arms 11 and 21 as examples, by simulating the submodule open-circuit faults at different positions of different arms, the feasibility of the proposed method can be verified. Combining the above parameters and the previous analysis, the db6 wavelet is used in the wavelet analysis to analyse the two layers, and the second-layer detail coefficient is selected as the criterion. When the arm current of the M1 group is under normal...
operation, the maximum value of the second-layer detail coefficient obtained by wavelet analysis is $d_{n1,j,k} = 0.6$, while $d_{n2,j,k} = 0.3$ in the M2 group. The fault detection threshold coefficients of the M1 and M2 groups are $\eta_1 = 5$ and $\eta_2 = 3$, and the fault location threshold coefficients of the M1 and M2 groups are $k_1 = 1.3$ and $k_2 = 1.1$, respectively. The fault detection criterion $|d_{n,j,k}^{ex}| > |\eta_{ex}d_{n,j,k}^{ex}|$ occurs 10 times in 5 consecutive sampling periods, and the fault positioning delay is $T_q = 3$ ms.
5.2.1 Open-circuit failure of submodules 1 and 4 of arm 11

The open-circuit fault that occurred in submodules 1 and 4 of arm 11 is set at 3.5 s. The current waveform of each arm is shown in Figure 10(a). The current of each arm is distorted, and the detail coefficient is obtained by wavelet analysis. The wavelet analysis results are shown in Figure 10(b)–(d).

In Figure 10(b)–(d), \( S \) represents the original signal of the arm current, and \( d_2 \) is the second-layer detail coefficient obtained after wavelet transform. When a submodule open-circuit fault occurs, the maximum value of the detail coefficient \( d_2 \) changes, but the degrees of change in the different arms are different. Thirty-five milliseconds after the fault occurs, the detail coefficient of arm 11 exceeds the threshold \( |\eta_1 d_{1,k}^{n1}| = 3 \) for the first time, and \( |d_j| > |\eta_1 d_{1,k}^{n1}| \) occurs 10 times in the next 5 sampling periods, while the detail coefficients of other arms do not exceed the threshold. Therefore, arm 11 is a faulty arm, and the fault detection process takes 40 ms. At the end of fault detection, the fault location algorithm started immediately. The submodule capacitor voltage waveform of the faulty arm is shown in Figure 11.

As shown in Figure 11, at the beginning of the fault, all submodule capacitance voltages of the faulty arm increase. After 40 ms, the capacitor voltages of submodules 1 and 4 continue to increase, and other submodules begin to fluctuate within a certain range. At 3.54 s, the fault location algorithm starts. At this time, the capacitor voltages of submodules 1 and 4 are greater than the threshold \( k_1 U_{1sm} = 1300 \text{ V} \). After a delay of 3 ms, the voltage does not fall below the threshold. It is determined that submodules 1 and 4
are fault submodules. The entire fault detection and location process takes 43 ms to accurately position the faulty submodule.

5.2.2 Open-circuit failure of submodules 1 and 7 of arm 21

The open-circuit fault in submodules 1 and 7 of arm 21 was set to occur at 3 s. The current waveform of each arm is shown in Figure 12(a), and the detailed coefficient of each arm current is obtained by wavelet analysis (the result is shown in Figure 12(b)–(d)).

From the wavelet analysis results in Figure 12(b)–(d), it can be seen that the current detail coefficient of arm 21 exceeds the threshold $|\eta_{2j,k}^d| = 0.75$ for the first time after the fault occurs for 3 ms, but the threshold is not exceeded in the next cycle. At 3.005 s, the detail coefficient is again greater than the threshold, and $|\eta_{2j,k}^d| > |\eta_{2j,k}^d| = 0.75$ occurs 10 times in the next 5 cycles, while the detail coefficients of the other arms do not exceed the threshold; thus, arm 21 is determined to be the fault arm, and fault detection takes 10 ms. After fault detection is completed, the fault location algorithm starts immediately; the submodule capacitor voltage waveform of arm 21 is shown in Figure 13(a) and (b).

As shown in Figure 13, at 3.01 s, the fault location algorithm starts, and the capacitance voltages of all submodules are less than threshold $k_2U_{2sm}^s = 1100 \text{ V}$; at 3.02 s, the capacitance voltages of submodules 1 and 7 exceed the threshold and still exceed $k_2U_{2sm}^s = 1100 \text{ V}$ after 3 ms, while the capacitance voltages of other submodules are not greater than the threshold; thus, we can determine that submodules 1 and 7 are fault submodules. The whole fault detection and location process takes 23 ms to locate the fault submodules accurately.

From the above two simulation cases, it can be seen that the proposed method quickly and accurately determines the locations of submodule open-circuit faults, and it can diagnose multiple submodule open-circuit faults of different arms and different positions in an H-M2DCT. Fault diagnosis takes approximately 40 ms.

5.3 Comparison with other methods

The advantages and disadvantages of the proposed method are shown in Table 3 and compared with other MMC and H-M2DCT fault diagnosis methods.

Specifically, references [19–20] are representative of the first category, references [15] is representative of the second category, and references [16] is representative of the third category.
Fault diagnosis time is an important parameter for assessing the advantages and disadvantages of various methods. References [12,21] used a sliding mode observer to detect and locate the submodule fault, and the fault diagnosis required 100 ms. In reference [13], a Kalman filter was used to detect the submodule fault, and the submodule capacitor voltage value comparison method was used to locate the submodule. However, the fault diagnosis time exceeded 100 ms. In reference [15], a method based on a clustering algorithm and capacitor voltage capacitance calculation was proposed to diagnose the fault of an MMC submodule, which required more than 10 ms. In reference [16], a fault-tolerant configuration of an MMC submodule based on a state machine was proposed. The method can locate the fault submodule within 5 ms, but it requires several voltage sensors, and the algorithm is complex. The maximum time of the proposed method is 40 ms. Compared with other methods, the detection time is greatly improved compared with a sliding mode observer and Kalman filter; it is slightly slower than other artificial intelligence methods or the scheme of adding measurement equipment.

The topological structure of different transformers is different, and the parameters of the components are also different, especially the bridge arm inductance, which has a great impact on the fault characteristics. With this difference in inductance, the maximum value of the detail coefficient $d_{v_{nk}}$ of the whole bridge group in normal operation is also different. At this stage, the scheme does not need to know the internal topology of the DC transformer but needs to carry out a test or direct theoretical analysis for a specific transformer to obtain the maximum value of the detail coefficient of the full bridge group in normal operation; then, the action setting value is calculated according to $d_{v_{nk}}$. Of course, on the basis of the mature scheme, the floating threshold method can be adopted to measure $d_{v_{nk}}$ in real time before a fault, and then the action criterion will float.

### TABLE 3 Comparison of open-circuit fault diagnosis methods for submodules

| Fault diagnosis method                     | Advantages                                                                                                                                 | Disadvantages                                                                                       |
|--------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| Parametric design-based approach           | ① No need to build complex mathematical models for open-circuit faults of submodules.                                                    | ① Need to design accurate prediction equations.                                                      |
| Artificial intelligence-based approach     | ② Simple logic and high reliability in fault diagnosis.                                                                                   | ② Unable to assess a large number of submodules with high AC frequency.                             |
| Method based on adding measurement circuit | ① No need to design accurate prediction models.                                                                                         | ② The fault diagnosis has low reliability and is prone to improper judgement.                      |
|                                             | ② Fast fault diagnosis.                                                                                                                  | ② The location of the faulty submodule cannot be pinpointed.                                         |
|                                             | ① Simple logic and easy to implement.                                                                                                    | ① Adding a large number of extra circuits leads to complex equipment structure and affects the reliability of the equipment. |
|                                             | ② Fast fault diagnosis.                                                                                                                  | ② Damage to extra circuits can cause malfunction of equipment relay protection.                     |
| Method proposed in this article            | ① No need to build complex mathematical models for open-circuit faults of submodules.                                                    | ① Low economy.                                                                                       |
|                                             | ② No need to design accurate prediction models;                                                                                         | ② When the system parameters change, the optimal wavelet function needs to be selected again.       |
|                                             | ③ No need to start the submodule measurement circuit for a long time.                                                                     |-------------------------------------------------------------------------------------------------------|
|                                             | ④ Adapt to high-frequency workplaces.                                                                                                   |-------------------------------------------------------------------------------------------------------|
|                                             | ⑤ Fast fault diagnosis and high reliability.                                                                                             |-------------------------------------------------------------------------------------------------------|
according to the maximum value of real-time measurement to realise the self-adaptation of this scheme to various DC transformers.

In particular, different detection schemes have their own advantages. In application, multiple methods can be combined to achieve the effect of learning from each other to ensure the safety of the equipment.

6 | CONCLUSION

Based on an analysis of open-circuit faults in H-M2DCT submodules, a fast detection method of open-circuit faults in the H-M2DCT submodule based on wavelet analysis is proposed, and a fault location method based on the capacitance voltage amplitude of the submodule is proposed to reduce the number of calculations required for fault location. The simulation model meets the practical requirements, and the results show that the proposed method can detect open-circuit faults in multiple submodules in different locations within 40 ms. This method requires no established mathematical functions or additional sensors, and the calculation process is simple and easy to implement in microprocessors. The control strategy is an important factor affecting the fault characteristics of H-M2DCTs. The next step of this research is to study whether this method is suitable for the detection and location of open-circuit faults in H-M2DCT submodules under different control strategies to explore a more reliable and efficient diagnosis method for open-circuit faults in H-M2DCT submodules.

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