# A Review of Fault Protection Research on Flexible DC Grids

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## Abstract

**A flexible DC grid based on a modular multilevel converter has the advantages of being able to realize self-phase conversion, independent control of active and reactive power, multi-energy power supply, and multi-drop point receiving power, which is one of the most promising directions for the development of future energy internet. Compared with the conventional DC transmission system, the fault characteristics of a flexible DC grid are more complex, and the corresponding fault identification is also more difficult. The current research status of fault identification methods for flexible DC networks at home and abroad is comprehensively introduced from different analytical perspectives of fault identification methods, and different fault identification methods are summarized. It also summarizes the different fault identification methods and puts forward suggestions for further research on the fault identification methods of flexible DC networks.**

## Keywords

**Flexible DC Grid; DC Fault Classification; Fault Detection and Identification; Traveling Wave Principle; Neural Network.**

## 1. Introduction

Traditional DC transmission technology is a one-way transmission technology, the current of the transmission line can only be in one direction. Ac lateral system provides commutation current, resulting in a lot of reactive power consumption, resulting in output voltage and current containing large harmonics, need to install a filter device. Moreover, when the AC side is disturbed, it is easy to cause commutation failure, and it cannot supply power to the weak source or passive network. Flexible DC transmission technology with the development of power electronics technology, the use of a Voltage Source Converter (VSC), can achieve two-way control and regulation of the transmission line, the current direction can be forward or reversed, to achieve flexible response and regulation of the power load and power supply side. Flexible HVDC technology independently controls active and reactive power, not only flexible, high-speed, and accurate power control, but also can realize multi-energy power supply, complementarity, and absorption. Compared with traditional HVDC technology, flexible HVDC technology has better stability and response speed, and is a key technology to solve new energy problems and grid-connection [1]. China's current energy status is generally more in the west, less in the east, and less in the north, but the power load is concentrated in the more developed central and eastern regions, the use of coal transportation time and a lot of financial resources, research large capacity, long-distance flexible transmission method is imperative. With the improvement of voltage level and transmission capacity and the long transmission distance, the high cost of cable lines [2], overhead lines have obvious advantages in terms of investment cost and transmission capacity, so more overhead lines are used to replace cable lines. Overhead lines are exposed to the natural environment, which greatly increases the probability of failure. The fault of

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transmission lines will pose a serious threat to the stable operation of the whole system. Therefore, it is of great significance to study the fault identification and protection methods of flexible HVDC lines.

At present, there are the following important challenges in the line fault identification direction of flexible HVDC:

1) DC failure is inevitable. Due to the characteristics of "low damping and weak inertia" in the flexible DC power grid, the short-circuit current rises very fast after the failure of the DC transmission line, and the fault identification is required to be completed within milliseconds. This puts forward a very high requirement for the quick performance of fault identification.

2) In order to ensure accurate fault identification, the existing protection method will increase the protection threshold, but this will reduce the ability of the protection method to withstand high-resistance faults, and it is necessary to balance the fault selectivity and high-resistance ability;

3) Sensitivity requires accurate identification of various faults, which will be affected by the sampling frequency. The higher the sampling frequency, the richer the fault data extracted, and the higher the sampling frequency will lead to higher sensitivity;

4) Noise interference and lightning interference will affect the reliability of the fault identification method, and the interference of noise and lightning strikes should be considered when identifying faults.

## 2. Flexible DC Power Grid and its Fault Characteristics

### 2.1 Basic Concept of Flexible DC Power Grid

The basis of a flexible DC power grid is DC power transmission, and there is no clear definition of a DC power grid at present. It can be understood that multiple converter stations are connected together to form a DC power grid. For example, as defined in the literature [3], a network tributary power grid containing multiple DC terminal nodes and connecting with the AC system is established. Literature [4] indicates that the DC power grid is composed of converters, DC transformers, DC circuit breakers, DC power flow controllers, and other devices, and relies on transmission lines to connect each converter station to achieve power transmission. China's Zhangbei flexible DC power grid is the first DC power grid project with network characteristics in the world, and its equivalent topology is shown in Fig 1. Four converter stations in Kangbao, Zhangbei, Fengning, and Beijing are connected to form a mesh structure.

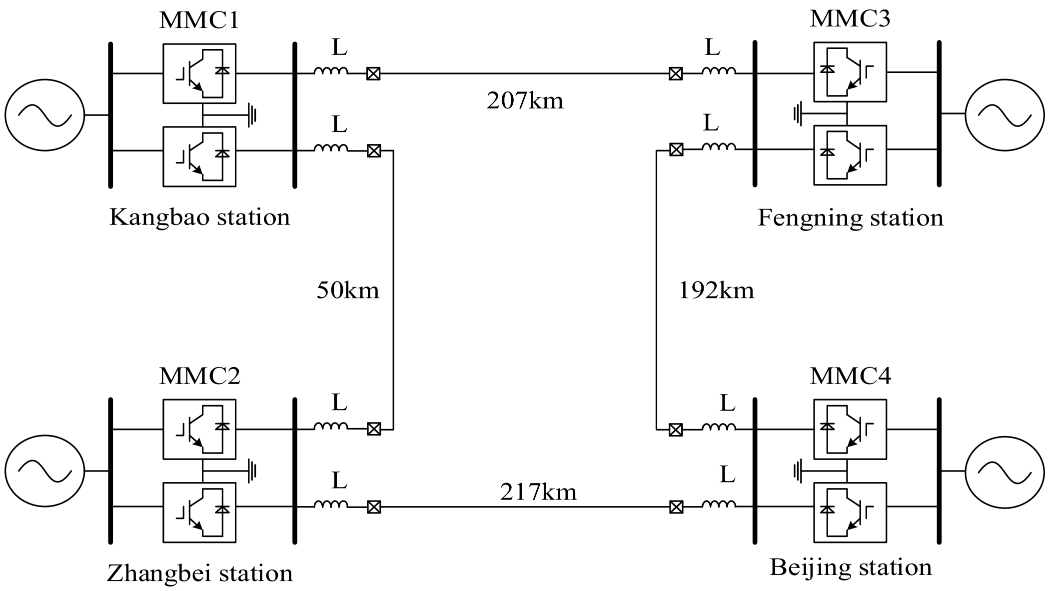


**Fig. 1** The equivalent topology of Zhangbei flexible DC power network

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## 2.2 Fault Analysis of Flexible DC Power Grid

The fault types of flexible DC power grid are composed of AC side fault, converter fault, and DC transmission line fault. The main wiring of the flexible HVDC system is divided into a true bipolar system and a pseudo-bipolar system. When the HVDC line of the true bipolar system has a single-bipolar fault, the voltage decreases and the current increases rapidly due to the capacitor discharge of the submodule of the converter. The fault principle of the pseudo-bipolar system is the distributed capacitor discharge of the transmission line, and the bipolar fault is also manifested as the voltage reduction and the rapid rise of the current, but the unipolar fault is manifested as the fault electrode voltage reduction and the healthy electrode voltage increase, and there is no continuous fault current. Therefore, the pseudo-bipolar model is taken as an example to analyze the fault characteristics of single-pole grounding faults and bipolar short-circuit faults.

### 2.2.1 Single Pole Ground Fault

When a single-pole grounding fault occurs in the HVDC line of a pseudo-bipolar system, the special modular multilevel technology and special grounding mode of the flexible DC power grid make the converter capacitor have no ground loop and the capacitor does not discharge, so the average capacitor voltage of the submodule can remain unchanged as Uc and thus Udc. However, the fault makes the grounding line voltage change to 0 and changes the zero potential point of the converter. When the positive line is grounded, the positive line voltage UpL and the negative line voltage UnL are respectively.

$$\begin{cases} U_{pL} = 0 \\ U_{nL} = -U_{dc} \end{cases} \tag{1}$$

That is, when a ground fault occurs in the positive line, the voltage between the positive and negative electrodes of the line is unchanged, the positive voltage becomes 0, and the negative voltage changes from -Udc/2 to -Udc. When the negative line is grounded, it is similar to the positive grounding fault, the voltage between the positive and negative terminals is unchanged, the positive voltage changes from Udc/2 to Udc, and the negative voltage is 0. The short circuit current of a single-pole grounding fault is very small because the ground point changes the zero potential point, the fault pole voltage of the whole system becomes 0, and the non-fault pole voltage becomes 2 times of the original.

When a single pole ground fault occurs in a DC line, the ground point voltage changes to 0 instantaneously, and a transient voltage traveling wave is generated. As shown in Fig 2, the transient traveling wave propagates from the fault point to both ends of the line and emits and refracts between the fault point and the bus. The superposition of multiple reflections and refractions of transient traveling waves will produce rich high-frequency transient components of line voltage.

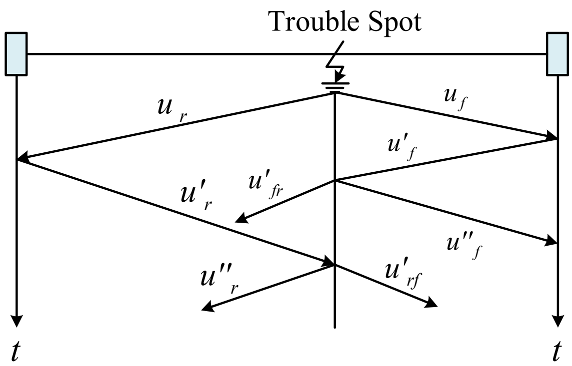


**Fig. 2** Unipolar ground fault traveling wave grid diagram

### 2.2.2 Bipolar Short Circuit Fault

When the bipolar short-circuit fault occurs in the flexible DC power network, both the positive and negative lines show a voltage drop and the current rises sharply. The bipolar short-circuit fault is one of the most serious faults in the flexible DC power grid, which can cause serious overcurrent and affect the system's operation. The fault transient process of bipolar short-circuit fault can be divided into two stages: submodule capacitor discharge and bridge arm inductance continuous current and AC side current feed.

In the sub-module capacitor discharge stage, the sub-module capacitor is in the state of short-circuit discharge, and there are factors such as bridge arm inductance that hinder the current fed into the AC side fault point and the time period of this stage, and the impulse current generated by it constitutes the main part of the fault current. When other system parameters are fixed, the larger the submodule capacitance is, the faster the fault current rises and the larger the amplitude is. The larger the bridge arm reactance, the slower the fault current rises and the smaller the amplitude. The converter is not locked, the submodules are still running normally, and the two groups of submodules that discharge alternately in each phase are approximately regarded as the parallel state, so the bipolar short-circuit fault can be equivalent to an RLC second-order discharge circuit. At this stage, the capacitor voltage of the submodule drops rapidly and the current of the DC line rises rapidly.

When the bridge arm current exceeds the setting value of the IGBT overcurrent protection, the IGBT will lock when the bridge arm current exceeds the setting value of the IGBT overcurrent protection. At the same time, when the DC line detects a DC fault, it will disconnect the DC circuit breaker or block the converter to protect the system device. When the submodule is just locked, the fault current mainly consists of two parts: the inductive current of the bridge arm and the current fed into the AC side. Due to the continuous current action of the inductor of the bridge arm, the diodes of the upper and lower bridge arms are kept on at the same time until the current of the inductor of the bridge arm decreases continuously to 0, and only one diode of the upper and lower bridge arms is switched on, and the converter operates in the form of uncontrolled rectification. The DC fault current enters the stable stage, and the fault current consists only of the current fed into the AC side. At this time, the DC load is composed of excessive resistance and short-circuit line impedance with a very small impedance value, and the system is still seriously harmed by overcurrent. It should be noted that the input current of the AC side is negligible compared with the capacitor discharge current of the submodule, and the capacitor discharge process of the submodule is mainly analyzed.

## 3. Fault Identification Method of Flexible DC Power Grid

At present, many fault identification methods for HVDC lines have been proposed at home and abroad, which can be roughly divided into four methods based on time domain feature, frequency domain feature, traveling wave principle, and intelligent algorithm according to different analysis angles.

### 3.1 Fault Identification Method based on Time Domain Feature

When a DC short-circuit fault occurs, the basic characteristic of a flexible DC power network is that the current increases and the voltage decreases. The fault identification method based on time domain features mainly detects the amplitude change or incremental change rate of voltage/current on the DC line for fault identification and location.

The literature [5,6,7,8,9,10] uses the voltage conversion rate on the DC line after the fault occurs to identify and locate the fault. Reference [5] uses DC line port voltage for fault identification. In literature [6], the voltage gradient change of three consecutive sampling points is used as the starting criterion for fault identification, the threshold is adjusted according to the weakest fault in the area and the most serious fault outside the area, and then the faults inside the area and outside the area are distinguished by detecting the voltage change rate on the line side of the current-limiting reactor. Literature [7] uses the magnitude of the voltage change rate on the current-limiting reactor to identify the fault line, and then decouples the DC voltage at the fault place into 0 mode and 1 mode components through phase-mode transformation, and uses the 0 mode component to determine the fault pole. Literature [8] uses the product of the DC voltage change rate on the positive and negative line current-limiting reactor to judge the fault line. If the product is negative, the fault exists, and the difference is used to distinguish the fault type. If the difference is zero, it is a bipolar short-circuit fault. The difference is exactly a positive grounding fault; If the difference is negative, the negative grounding fault occurs. Literature [9] built a simulation model to analyze the influence of current limiting inductance, fault location, fault type, and measurement time constant on voltage conversion rate, select appropriate fault threshold, identify fault type, and locate fault.

Similar to the fault identification method based on the DC voltage change rate, literature [11,12,13] proposes a fault identification and location method based on the DC current change rate. Literature [11] sets a threshold to identify faults based on the characteristics that the fault current rises rapidly when the fault occurs within the area and rises slowly when the fault occurs outside the area. However, the fault current of the single-pole grounding in the area may be smaller than the fault current of the double-tap short-circuit outside the area, which is prone to misjudgment. Literature [12] estimates the equivalent line inductance by measuring the current change rate at the initial time of the fault and then compares the set value to quickly determine the occurrence and location of the fault. In literature [13], overcurrent is used as the protection criterion, and the change rate of fault current is used to identify near-end faults and far-end faults.

The fault identification method based on time domain features can meet the requirements of rapid fault identification. However, due to the lack of an analytical solution for fault current in multi-terminal DC power grid and the weak anti-interference ability of the time domain algorithm, the sensitivity and reliability of fault identification are significantly reduced under interference such as noise or lightning strike, and it is easy to misjudge. In practical engineering, the time domain method is more used as the detection algorithm of flexible DC power grid protection fast start-up.

### 3.2 Fault Identification Method based on Frequency Domain Feature

The fault identification method based on the frequency-domain feature is proposed to solve the problem of insufficient anti-interference ability of the time-domain algorithm. The principle is to use the current limiting reactor on both sides of the line to block the high-frequency component and form the fault identification criterion. In literature [14], the magnitude of current high-frequency transient energy is used to distinguish faults in and out of the region. The principle is that when a fault occurs, the high-frequency reactor will exhibit a large impedance value, which is equivalent to adding a high-frequency block boundary. The transient energy of faults inside and outside the region has obvious characteristic differences, which can be used as a criterion for fault identification.

The fault identification method based on frequency domain characteristics depends on the measured DC voltage, current, and other transient electrical gas, but in some fault cases, the detected transient electrical gas difference is relatively small, so it is necessary to carry out corresponding signal processing for the transient electrical gas to extract the fault characteristic quantity, so as to achieve more accurate fault identification. Wavelet transform is one of the most widely used signal processing methods for DC power grid fault detection because it can perform multi-scale singularity analysis of signals and eliminate noise signals, and can be used for transient signal decomposition and feature extraction [15]. Literature [16] takes DC reactors at both ends of the line as the boundary, extracts high-frequency components based on wavelet transform, and uses the amplitude ratio of voltage transient components on both sides to judge out-of-area faults, which can reliably distinguish forward in-area faults from back-side DC faults. This method belongs to the longitudinal protection, and misjudgment may occur if an inappropriate protection time window is selected. Literature [17] uses discrete wavelet transform to process voltage signals, obtains high-frequency transient energy through integral transformation, and then uses wavelet current energy and voltage change rate for fault identification and fault pole selection. However, when the DC fault occurs on the back side of the protection device, the current limiting reactor will block the high-frequency component of the voltage so that it cannot distinguish between the forward zone fault and the back side DC fault. When

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the characteristic quantity in the frequency domain is analyzed and processed by mathematical tools such as wavelet transform, the detail coefficient of wavelet transform belongs to the high-frequency component and the noise also belongs to the high-frequency component, so it is necessary to analyze its anti-noise ability. In literature [18], fault identification is carried out based on the voltage difference of reactors, fault detection is carried out by the sum of the voltage of positive and negative reactors, and fault pole selection is carried out by the difference of voltage difference amplitude of positive and negative reactors. Both criteria are constructed by integrating method, which has strong anti-noise ability. Literature [19] collects the transient current and transient voltage on the line boundary, obtains the transient harmonic energy of a specific frequency band, uses the transient harmonic energy difference to identify faults inside and outside the region, and uses the transient harmonic energy ratio to select fault poles. On this basis, literature [20] uses the transient energy of fault current and voltage in the whole frequency band to identify faults, without the need to extract characteristic frequency bands, and the operation time is faster.

The current fault identification methods are based on frequency domain characteristics, first, the threshold setting value lacks of theoretical basis, mainly through simulation results, and can not be accurately calculated, line parameters such as the transition resistance size, fault location, etc., when the frequency domain signal of electrical volume is different; Second, the acquisition of the fault frequency domain signal needs a suitable sampling time window, if the required sampling time window is too long, it is difficult to meet the requirements of rapid fault identification; Third, most of the criteria require energy signals in high-frequency bands, and the selection rules of frequency bands have no theoretical basis, and the selection of frequency bands has a great impact on fault identification. Therefore, the reliability of fault identification methods based on frequency domain features needs to be improved.

### 3.3 Fault Identification Method based on Traveling Wave Principle

The fault traveling wave is generated when the fault occurs in the DC transmission line. The fault traveling wave propagates close to the speed of light in the distributed parameter line and contains rich transient fault information. Therefore, the initial fault traveling wave propagating from the fault point to both ends of the line at the initial time of fault occurrence can be used for fault identification.

The fault identification method based on the traveling wave principle uses different mathematical methods to extract high-frequency components such as amplitude, polarity, and duration of fault traveling wave for analysis and realizes fault identification and location. Literature [21] identifies faults inside and outside the region by detecting the polarity and amplitude of the initial wave head of the voltage traveling wave on both sides of the current reactor within the time limit of DC fault occurrence. Literature [22] combines the principle of traveling wave and differential protection with the dual advantages of relative rapidness of traveling wave protection and absolute selectivity of differential protection and identifies faults inside and outside the region by comparing the polarity and amplitude of the initial fault traveling wave detected on both sides of the line. Literature [23] first detects the change of electrical capacity of the forward traveling wave head and then extracts the change of fault current using the characteristic admittance of frequency to distinguish the faults within and outside the region. In literature [24], the change in the electrical capacity of the reverse traveling wave head is first detected, and then the intermediate differential mode and common mode components are extracted to identify the fault types. Since this method is only sensitive to the traveling wave in the specified protection direction, additional protection criteria of other electrical volumes are needed to improve its reliability. Literature [25] carries out fault identification on three characteristic quantities based on the traveling wave, namely voltage change rate, voltage transformation quantity, and current transformation quantity. The detection functions corresponding to each characteristic quantity complement each other to reduce the interference of non-fault disturbance and improve the reliability of fault line and pole selection.

For the fault traveling wave, we can also use the wavelet transform and other mathematical methods to extract the characteristics of transient electric gas such as voltage and current, and form a criterion

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to identify the fault type. Literature [26] analyzed in detail the propagation of the initial fault traveling wave at the boundary of the DC line and used the wavelet transform mode maximum to extract the traveling wave head to identify the fault type. In literature [27], discrete wavelet transform and wavelet energy ratio of directional traveling waves are used to determine the fault line.

The fault identification method based on detecting the initial fault traveling wave head can satisfy the speed and selectivity well, but it still lacks reliability. The overhead DC line interfered with by lightning strikes will generate a larger value of the interference traveling wave with the same polarity as the fault traveling wave, which will lead to misjudgment. Aiming at the problem that it is difficult for traveling wave protection to distinguish lightning interference from real faults, literature [28] uses wavelet energy moment to detect the magnitude of high-frequency band energy to distinguish lightning interference from real faults. Literature [29] distinguishes the two by detecting the correlation between voltage and current.

The above literature is based on single-ended electrical capacity fault identification methods, The speed of fault identification is very fast but the reliability is poor. Literature [30,31,32] proposes a traveling wave detection method based on double-ended electrical capacity, which determines the type and location of faults by calculating the time interval between any two endpoints of traveling wave propagation. The detection method of two-terminal electrical volume mainly aims at the accuracy of fault location, but for long transmission lines, the communication time on both sides of the line will have a delay effect.

The electrical information used by traveling wave protection will decay with time, and it does not have steady-state characteristics. Moreover, it is not sensitive enough to be susceptible to interference such as noise in the case of high-resistance faults, which should be fully considered in practical applications [33].

### 3.4 Fault Identification Method based on Intelligent Algorithm

With the development of artificial intelligence, intelligent algorithms are gradually applied to fault identification of transmission lines. Literature [34] proposes an algorithm based on an artificial neural network (ANN), which uses four neural networks for fault identification of HVDC transmission systems, and its workload is large and complex. For the VSC-HVDC system, literature [35] collects fault current signal, uses windowed discrete Fourier transform on the fault signal to obtain the spectrum component of the signal, and uses the real part of the spectrum component to represent the amplitude at different frequencies in the windowed signal, thus generating spectrum. The frequency spectrum is used as the input of the neural network to recognize the fault type. Compared with the literature [34], the scheme adopts three neural networks successively to realize fault detection, fault classification, and fault location functions. Literature [36] uses wavelet transform and fuzzy C-means algorithm to extract fault features. However, this method does not consider the influence of fault resistance and noise interference. Literature [37] proposes a protection scheme based on a fuzzy control algorithm, which uses a multi-layer wavelet transform to extract fault features and realizes fault recognition function through training weights. However, the maximum detectable fault resistance is only 50Ω. A protection scheme based on machine learning was proposed in the literature [38]. However, this method requires a large number of current sensors to be installed along the line, increasing the investment cost. Based on a branch-structured convolutional neural network (BR-CNN), literature [39] proposed an auxiliary fault identification method to distinguish positive grounding faults from lightning strike interference. The voltage and current feature matrix was constructed as the input matrix of BR-CNN, and the higher-order local features of input data were extracted layer by layer to make comprehensive use of voltage and current information. Through the independent learning of the model, the nonlinear mapping relationship between input and output is constructed, and the real fault and lightning strike interference can be reliably distinguished.

Compared with the non-intelligent fault identification method, the fault identification method based on an intelligent algorithm avoids the complicated threshold determination and calculation process and has good rapidity and selectivity, but it is still in the primary stage of research. Its application in practical engineering needs further research.

### 3.5 Comprehensive Fault Identification Method

The current fault identification methods of flexible DC power grids are not limited to using only one method, but more comprehensive advantages of various methods. For example, in literature [40], firstly, the voltage and current flow of positive and negative terminals of a line are collected, the inverse traveling wave of line mode voltage and ground mode voltage are calculated by using Kellenberr transform decoupling, and then the characteristics of faults inside and outside the area are analyzed by time-frequency transform. The S-transform is used to establish an energy spectrum matrix, and the fault types are identified according to the similarity of the energy spectrum matrix. Literature [41] uses the current mutation as the starting criterion of protection, collects the voltage and current data 2ms after the fault, calculates the inverse traveling wave, and inputs the deep learning model as sample data for training and testing. The method adopts an adaptive artificial intelligence algorithm to avoid complex calculation and threshold setting and uses traveling waves. The detection time is only 2ms to meet the requirement of fast protection.

## 4. Conclusion

The fault identification method is the key to the development of a flexible DC power grid. Based on the analysis of the fault characteristics of flexible DC power grid, this paper focuses on the analysis of the fault identification method of DC lines in flexible DC power grid, introduces and analyzes the existing research status at home and abroad in detail, and draws the following conclusions:

1) The fault identification method of the flexible DC power grid is the basis of the implementation of the fault protection scheme. Currently, the fault identification method mainly includes the fault identification method based on the time domain feature, the frequency domain feature, the traveling wave principle, and the intelligent algorithm. In practical engineering applications, two or more fault identification methods can be combined to form the fault identification of the whole system, and the fault identification method based on the time domain feature or the single-end measurement traveling wave protection method can satisfy the rapid fault identification. The sensitivity and selectivity of fault identification can be achieved by using the frequency-domain feature-based fault identification method and the two-terminal traveling-wave protection method.

2) In the process of fault detection and identification of flexible DC power grids, the fault characteristics should be fully considered, and the most suitable fault identification method for flexible DC power grids should be studied in combination with the latest signal processing algorithm for feature extraction to improve the reliability of the fault identification method.

3) Previous studies on fault identification methods of flexible DC power grids mainly focused on fault identification in a certain model, focusing on the selection of feature extraction methods and the establishment of fault identification criteria. In the following studies, we can try to apply neural networks to fault identification to verify the feasibility of this method in engineering or experiments. However, using the neural network method means that a large number of data sample characteristics are required, and a large number of data samples can be obtained through simulation.

To sum up, the research on fault detection and identification methods in DC power grids is still developing and improving, and experts and scholars at home and abroad have conducted in-depth research on the quickness and selectivity of fault identification strategies in flexible DC power grids, and have achieved certain results. In particular, traveling wave protection with fast-acting characteristics is one of the important directions for the future development of flexible DC power grid relay protection. At present, the fault detection and identification methods of flexible DC power grids are not mature, and the research on the reliability and sensitivity of fault identification is still relatively lacking, which is an urgent problem to be solved and needs more in-depth research.

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