Research Article

A DC Fault Location Method of Multiterminal Flexible DC Distribution Network

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Multiterminal flexible DC distribution network is a complex system made up of many power-electronic devices. Its diversified and comprehensive fault characteristics are featured by multiperiod and strong transient. This paper starts with investigating the mechanisms of typical DC short circuit faults of the MMC-based system. Then, a typical flexible DC distribution network is built in PSCAD to analyse the characteristics of its pole-to-pole short-circuit fault and pole-to-ground fault. With the aid of the above findings, a fault detection and location method is proposed with its effectiveness evaluated through simulations.

1. Introduction

With the development and utilization of distributed power generation, DC loads, such as electric vehicles, domestic appliances, intelligent buildings, and data communication systems, are accelerating their grid penetration. The grid connection of energy storage systems is also continuously promoted. Meanwhile, the increasing numbers of important and sensitive electrical and electronic equipment have high power quality requirements. In this context, the multiterminal flexible DC distribution network based on flexible DC power transmission technology is preferred for the development of an urban power distribution network [1, 2]. The application of a modular multilevel converter (MMC)-based flexible distribution network not only has improved the hosting capacity of the distributed generation (DG) systems and DC loads but also provides grid overload alleviation, reduced grid losses, and strengthened security and stability of grid operation [3, 4]. Moreover, the application of flexible DC devices can optimize the operational control capability of the system network, and improve the control capability and security of the power distribution network. The operational control scheme and the decision-making method of the flexible DC devices have important meanings for improving the security and economy of the power distribution network.

One of the toughest challenges that the flexible DC power distribution currently facing is the applied protection technology which is determined by the network topology, control scheme, and fault characteristics. Wu et al. and Dai et al. [5, 6] analyse the impact of different topologies of the multiterminal flexible DC distribution network on the protection schemes. Li and Su and Zhou et al. [7, 8] discuss the typical protection divisions and the fault types of the flexible DC power distribution network. Gao et al. [9] discuss the potential faults within the MMC and the corresponding protection technology. Zeng et al. and Meng et al. [10, 11] investigate the impacts of AC-side faults of the flexible DC distribution network on the DC protection scheme. Liang et al. [12] study the impact of the flexible DC distribution network on the differential protection of the AC power lines. Sano and Takasaki [13] investigate the protection coordination among different zones of the flexible DC distribution network and the corresponding protection setting calculation. Yue et al. [14] analyse the impact of wind farm integration on the system characteristics and the protection and control system of the flexible DC distribution network.
Some existing literature studies have studied the fault location methods of the flexible DC distribution network to varying degrees. Based on the high controllability of hybrid modular multilevel converter (MMC), a fault location method of the flexible DC distribution network based on fault current active control is proposed by injecting high-frequency reverse current at a specific frequency in [15]. By using the positive and negative voltage gradients to identify fault types and fault poles, a new fault location method for medium voltage flexible DC distribution lines based on the slope of the transient current waveform is proposed in [16]. Sun et al. [17] analyse the transient characteristics of bipolar short-circuit fault in the MMC flexible DC distribution network and proposes an accurate fault location method based on the initial transient current after submodule locking. In [18], the prony algorithm is used to extract the damping coefficient and characteristic frequency of capacitor discharge current, and a single-end fault location method based on current injection technology is proposed. A comprehensive fault location method based on differential protection and multipoint direction information is proposed in [19], and a DC distribution network protection device with a high sampling rate and a multitype analog interface is developed. Based on natural variation characteristics and curvature of DC under fault transients, a new scheme that could identify faults with different high resistances quickly and meet the speed and reliability requirement of the DC distribution system is proposed in [20]. Gao et al. [21] proposes a fault location method based on transient DC currents of the blocked converters. It is noticed that the protection technology of the medium voltage DC side of the flexible DC distribution network is not well investigated in the existing literature.

The DC faults of MMC-based flexible DC distribution network can be categorised into three types including the open-circuit fault (OC fault), pole-to-ground short circuit fault (PG fault), and pole-to-pole short-circuit fault (PP fault). Considering the fact that the AC side neutral point of MMC is typically grounded through the high-impedance path, the fault current is not obvious under the OC fault or PG fault, indicating that OC fault and PG fault are less harmful to MMC. Compared to the OC fault and PG fault, the fault current of PP fault is featured by high peak value and a fast-climbing rate, and provides direct damages to the submodules of MMC. The PP fault is now regarded as the most severe fault to the MMC-based flexible distribution network.

The paper is structured as follows. Section 2 discusses the short-circuit DC fault mechanisms of MMC-based DC system, with the characteristics of fault voltage and current illustrated by the simulation results of an MMC-based flexible distribution network. The protection division is also discussed in Section 2. To reduce the fault searching times and operational costs for the DC protection zone, fault detection method and fault location method are proposed in Section 2, with its performance evaluated through the short-circuit fault modelling of a practical flexible DC distribution network in Section 3. Section 4 concludes this study.

2. Materials and Methods

2.1. Short-Circuit DC Fault Mechanisms of MMC-Based Flexible DC Distribution Network

2.1.1. Mechanism and Characteristics of PG Fault. When PG fault occurs, the line-to-earth voltage of the grounded DC bus becomes zero, while the line-to-earth voltage of the ungrounded DC bus turns out to be twice its reference value in order to keep voltage across the positive and negative poles unchanged. Consequently, the PG fault can be easily detected from the voltage unbalance between the positive pole and the negative pole of the DC bus. Additionally, the fault location of the PG fault has a negligible impact on fault characteristics. The PG fault is divided into two stages according to the blocking time instance of MMC. Before MMC is blocked, the fault current is made up of two parts including the SM capacitor discharging current (the dominant part) and the AC feed-in current, with a current flowing path, as illustrated in Figure 1. As in Figure 1, where the negative pole is grounded, both the SM capacitor of the lower bridge arm and the AC system provide fault current to the fault location. The SMs of the lower bridge arm switch their operating states between on and off. The DC capacitor of on-state SM discharges through the path made up of its IGBT T1, Diode D2 of off-stage SM, the AC system, and the fault point. After MMC is blocked, the capacitors of SMs stop discharging, and only the AC system contributes to the fault current. The AC system discharges through the diodes of SMs. Figure 2 shows the PP voltage, the positive pole-to-ground (PG) current, and the negative pole-to-ground (NG) current of the DC output of an MMC-based system operating under PG fault. It is obvious that PP voltage only slightly decreases and is able to quickly recover to rated value after the fault is cleared, suggesting that the system is still capable of delivering active and reactive powers to the rest of the system.

2.1.2. Mechanism and Characteristics of PP Fault. The PP fault on the DC-side of MMC can be divided into two stages, the capacitor discharging stage and the uncontrolled rectifying stage depending on whether the MMC is blocked or not, as in Figure 3. Before the MMC is blocked, the SM capacitor discharges through the connected IGBTs, the fault point, and the AC system, resulting in a significant drop of the PP voltage and an apparent increase of the PG current. Figure 4 shows the simulated PP voltage, PG current, and NG current of a modelled MMC system under PP fault. As the PP voltage drops to a value close to zero, the system is unable to deliver power to the rest of the system. To avoid the SMs being damaged from the high PP fault current, the SMs will be blocked by their own protection with their capacitors being isolated. Afterwards, the SM capacitors stop discharging, and the MMC can be approximately equivalent to a three-phase uncontrolled rectifier. The fault current mainly refers to the current feeding from the AC system, and the fault characteristics are affected by the fault location.
Due to the limited overcurrent and overheating tolerance of IGBTs, the DC breakers have to break the fault current before the voltage of SM capacitors drops to zero (i.e., before the capacitor discharging stage is finished). After the MMC is blocked, the DC breakers have to further isolate the fault lines to prevent the further voltage drop of the SM capacitors. In this way, the SM capacitors can be quickly charged to their rated value after the fault is cleared, which is beneficial to the recovery of the MMC system.

2.1.3. The Protection Division of Flexible DC Power Distribution Network. The topology of a typical flexible DC power distribution network is illustrated in Figure 5, consisting of the MMC, double active bridges (DABs), DC-AC converters, power distribution lines, and switches. Its protection can be divided into five different zones including the front-end AC protection zone, the front-end DC protection zone, the DAB protection zone, the back-end DC protection zone, and the back-end AC protection zone. Specifically, the front-end AC protection zone is from the incoming lines of the main AC power supply to the outgoing lines of the MMC. The front-end DC protection zone is from the outgoing lines of MMC to the incoming lines of DAB. The back-end DC protection zone is from the outgoing lines of DAB to the incoming lines of an inverter, with the outgoing lines of DC loads included. The back-end AC protection zone is from the outgoing lines of inverters to the outgoing lines of AC loads. The proposed fault detection and location method in the next section is applied to the PG short-circuit fault and PP short-circuit fault within the medium voltage front-end protection zone.

Figure 1: The current flowing path for MMC under PG fault. (a) Before MMC is blocked. (b) After MMC is blocked.

Figure 2: The PP voltage, PG current, and NG current of a modelled MMC under PG fault.
2.2. DC Fault Detection and Location Method

2.2.1. Analysis of DC Fault Equivalent Circuit. When faults occur within the front-end protection zone, the fault lines can be represented by the equivalent circuits of the network under steady-state operation and under faults. The equivalent circuit of the front-end protection zone under steady-state operation is shown in Figure 6, where the output of MMC and the input of DAB are represented by two voltage sources, $U_R$ and $U_I$ (with their currents denoted as $I_R$ and $I_I$, $I_R = -I_I$). The protection zone is the distribution lines between $R$ and $I$.

When the short-circuit fault occurs within the protection zone (i.e., the internal fault), the equivalent circuit can be represented by Figure 7, where the fault is represented by a voltage source $U_f$ and an equivalent resistance $R_f$. The fault current is denoted as $I_f$. The fault results in the variance of $I_R$ and $I_I$ represented by $\Delta I_R$ and $\Delta I_I$. When a fault occurs within the front-end protection zone, the fault current flows from the MMC and DAB to the fault location, implying the positive change of $I_R$ and $I_I$.

When the short-circuit faults occur outside the front-end protection zone (i.e., the external fault), the equivalent circuit is shown in Figure 8. Assuming the fault occurs at the left side of the protection zone boundary $R$, $I_R$ will turn from positive to negative, indicating a negative value of $\Delta I_R$. Similarly, $\Delta I_I$ turns from positive to negative when the external fault is at the right side of the protection zone boundary $I$. Accordingly, it is able to know whether the occurrence of the short-circuit fault is within or outside the protection zone according to the break variable of the current $I_R$ and $I_I$.

2.2.2. Fault Detection Method. During the process of defining the fault signal, the problems of difficult parameter identification and complex calculation exist. In this paper, the current direction criteria are based on the slope of the
current-break variables at the protection boundaries. Firstly, when the fault occurs, the real-time current at the protection zone boundaries is measured and recorded to obtain the current-break variables, $\Delta I_R$ and $\Delta I_I$. Secondly, the fault current characteristics can be extracted via a low-pass filter, with the current-break variables decomposed into the time-domain variables, $\Delta I_{R1}$ and $\Delta I_{I1}$. Then, the time instances, $t_R$ and $t_I$ for $\Delta I_{R1}$ and $\Delta I_{I1}$ reaching their maximums can be observed, with the corresponding actual current-break variables denoted as $\Delta I_{R1t}$ and $\Delta I_{I1t}$. The slope of $\Delta I_{R1t}$ and
If cosine similarity between bustness under nonideal practical conditions. Here, the proposed method is further modified to improve its ro-
synchronised and may be superimposed with noise. M'_he sending end and the receiving end may not be perfectly
in phase or not.

It is due to the fact that the data measured from the sending end and the receiving end may not be perfectly synchronised and may be superimposed with noise. The proposed method is further modified to improve its robustness under nonideal practical conditions. Here, the cosine similarity between \( k_R \) and \( k_I \) is calculated as in (4) by applying a sliding window. It is obvious that (3) and (4) are equivalent as both are aimed at deciding if \( \Delta I_{R1} \) and \( \Delta I_{I1} \) are in phase or not.

\[
\cos(k_R, k_I) = \frac{\sum_{i=1}^{n} (k_{R,i} \cdot k_{I,i})}{\sqrt{\sum_{i=1}^{n} k_{R,i}^2 \sum_{i=1}^{n} k_{I,i}^2}} \quad (4)
\]

2.2.3. Fault Location Method. As illustrated in Figures 7 and 8, the short-circuit fault can be represented by a fault source, injecting the fault travelling waves to both sides of the DC protection zone. The fault travelling wave is a type of complex signal containing a series of high-frequency components. When the fault travelling waves reach both sides of the distribution line, the detected current signal exhibits abrupt changes. The travelling wave reaches the protection zone boundaries when the current break occurs. Based on the above time difference, the propagation distance of the travelling wave can be calculated. By applying the mode decomposition to the measured fault travelling wave signal, a sum of intrinsic mode functions at different frequencies can be obtained. The average value of the signal can be calculated from its upper and lower enveloping lines. If the difference between the original travelling wave and its average value satisfies the local mean equalling zero and the number of zero points equalling the number of extreme points, the difference can be treated as the intrinsic mode function at the highest frequency, Imf1, which directly describes the variation process of the fault travelling wave. The steps of the fault location method are summarized below:

**Step 1.** Confirm the short-circuit fault occurring within the protection zone according to the current direction and sample the current at the protection zone boundaries

**Step 2.** Apply empirical mode decomposition to the sampled signals at the protection zone boundaries

**Step 3.** Assume a phase-to-ground short-circuit fault occurring at the F location of a dual-terminal system, as shown in Figure 9; the time required for the fault current travelling wave reaching the protection zone boundaries-M and N is \( t_n \) and \( t_m \); the length of the distribution line is \( L \), and the propagation speed of the fault current travelling wave is \( v \); the fault location can be calculated from (5) and (6). Indeed, the travelling wave method has strict requirements of sampling frequency and signal synchronization. Due to the inherent advantage of insensitivity to the variation of transition resistance, DC cable impedance, and system operation modes, the travelling wave-based method is still widely used in the fault distance measurement of the hybrid AC/DC network.

\[
S_{mf} = \frac{L}{2} - \frac{(t_n - t_m)v}{2} \quad (5)
\]

\[
S_{nf} = \frac{L}{2} + \frac{(t_n - t_m)v}{2} \quad (6)
\]

3. Results and Discussion

A flexible DC power distribution network is modelled in PSCAD, with its layout illustrated in Figure 10. It is based on the actual flexible DC power distribution demonstration project located at Zhejiang, Hangzhou. The flexible DC distribution network is connected to the upper grid (110 kV, 50 Hz) via the three substation transformers. The AC power is converted to 20 kV DC form through the three converter stations. Then, the 20 kV DC voltage is further stepped down to 700 V through a DAB converter. The DC and AC loads (wind turbines, PVs, energy storage systems, etc.) are integrated into the 700 V DC bus via proper DC/DC or DC/AC converters. Here, the distribution lines (0.8 km) between the converter station A and 20 kVDC bus are used as an example of the DC protection zone. As in Figure 10, three types of short-circuit faults are considered, including the positive-phase earth fault (F1), the negative-phase earth fault (F2), and the bipole short-circuit fault (F3).

3.1. Fault Detection Simulation. A positive-phase earth fault is simulated at the location F1 of Cable 1 in Figure 10. The fault is at the 5 s of the simulation with the duration...
equalling 1 s. The sampling frequency is set at 2 kHz with the simulated current differentials of the positive phase and the negative phase, as shown in Figure 11. As in Section 2.2.2, the cosine similarity between the current differentials at the protection zone boundaries is calculated via a sliding window (window length equals 5 ms). Then, the obtained cosine similarity is further processed, as shown in Figure 12 to provide a straightforward fault detection method. To further evaluate the robustness of the proposed approach under asynchronous or noisy input signals, the fault detection method is first tested under delayed synchrosignals (delay length varies from 0 to 10 ms), and then tested under signals superimposed with white noise (SNR varies from 0 dB to 40 dB). As in Figure 13, the proposed method can timely detect the fault if only the delay length is shorter than the length of the data processing window (here is 10 ms). Figure 14 shows the cosine similarity under noisy signals. It turns out that the proposed method has good immunity to noise with SNR above 10 dB.
Figure 11: The simulation results of the PG short-circuit fault. (a) The current rate of change of the positive phase of Cable 1. (b) The current rate of change of the negative phase of Cable 1.

Figure 12: The flowchart of calculating the cosine similarity between $k_R$ and $k_I$.

Figure 13: The cosine similarity under delayed synchrosignals.
We assume a PP short-circuit fault occurring between the positive and negative phases of Cable 1 (at the location F3) with the time instance and duration equalling 5 s and 1 s, respectively. The corresponding current rate of change of the positive phase and the negative phase is shown in Figure 15. The corresponding cosine similarity under delayed
synchrosignals and noisy signals is shown in Figures 16 and 17. It turns out that the proposed method can accurately detect the fault even under asynchronous or noisy input signals.

3.2. Fault Location Simulation. The fault location method is demonstrated on the simulation of the positive-phase earth fault at location F1 (Figure 10). Location F1 is set at the middle of Cable 1 while the length of Cable 1 equals 20 km. The fault starts at 3 s of the simulation and lasts 1 s. The simulated positive and negative phase currents at the sending and receiving ends are shown in Figure 18 together with their differentials. By applying (13) and (14), the time instances for the protection zone boundaries (M and N) receiving the travelling wave are calculated to be 3.000052 s (for both M and N), indicating the fault being located at the middle of the protection zone. It turns out that the calculated
fault location is the same as the setting value. As the DC distribution cable length is relatively low as opposed to the travelling wave speed, high sampling rate and data synchronization are required to accurately capture the travelling wave.

4. Conclusions
This paper first reviews the typical typology and operating mechanism of the MMC-based flexible DC power distribution network, with its protection division which is also briefly introduced. To minimize the fault searching time and the operating cost of the DC front-end protection zone, the fault detection method is proposed based on the current differentials and the corresponding cosine similarity. The good performance of the method is validated through tests under asynchronous and noisy conditions. Then, the travelling wave-based fault location method is proposed, with its performance evaluated through the DC fault modelling of a practical flexible DC power distribution network. It turns out that the proposed fault location methods can accurately determine the fault location. Although the travelling wave-based method has stringent requirements of data synchronization and sampling frequency, it is still widely used in the field of fault distance measurement because of its high precision and insensitivity to the variation of transition resistance, DC cable impedance, and system operation modes compared to other fault location methods, such as the impedance method and the intelligent algorithm. [22].

Data Availability
All data included in this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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