Analysis on characteristic of DC short-circuit fault in multi-terminal AC/DC hybrid distribution network

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Abstract: The AC/DC hybrid distribution network takes advantage of both AC and DC technologies. It is one of the most important forms of future distribution systems. However, currently few work has been done on the topology determination of this network, and its fault behaviour of DC short-circuit fault has not been clearly investigated yet. First, the tree, radial, and ring topologies of a three-terminal AC/DC distribution network are compared. Also the characteristics of fault currents in DC circuit breakers during a DC short-circuit fault are analysed in detail. Then the equivalent circuit models during the fault are established and accurate mathematical expressions of transient fault currents are deduced. Based on this, the influence of network topologies on the characteristics of fault currents is investigated thoroughly. Moreover, a method to determine the peak values and peak times of fault currents is presented which can simplify the selection of circuit components. The simulation results show that the fault currents of the radial topology have the lowest peak values and longest peak times, and the proposed method meets the requirements of both simplicity and accuracy. Finally, the influence of the key parameters on the proposed method is investigated comprehensively.

1 Introduction

In recent years, with the rapid development of distributed generation technology, the traditional AC distribution network has faced great challenges brought about by increasing renewable energy sources, diversified DC loads, and so on [1]. The DC distribution network can handle these problems more easily. However, it is unrealistic to replace the AC distribution network completely [2, 3]. Therefore, in order to take advantage of the existing AC distribution network and DC distribution network, the AC/DC hybrid distribution network has been proposed and will be one of the important forms of the distribution network in the future [4]. It is important to analyse the fault characteristics and design of a reasonable topology for the AC/DC hybrid distribution network, which can simplify the configuration and planning of the network.

At present, the researches on the AC/DC hybrid distribution network mainly focus on the design of control strategies [5]. Its fault characteristics are not quite clear, and the selection criteria of its topology have not been formulated yet. Yang et al. [2] analyse the fault characteristics of a two-level voltage source converter (VSC) and deduces the fault current expressions for different stages of the fault. However, the calculation method can be used only in a single VSC. Based on this, the approximate expressions of DC fault currents in a high-voltage direct current (HVDC) system are deduced in [3, 4]. However, the travelling wave method used in [3] is not suitable for the short transmission line in an AC/DC hybrid distribution network.

Furthermore, the topology of an AC/DC hybrid distribution network has not been investigated thoroughly yet. References [5, 6] summarise the topologies of the current DC micro-grid and AC/DC hybrid micro-grid. The hybrid distribution network with an AC/DC hierarchical connection is proposed in [1], but it is just a proposal and has not been verified yet. In [7], the topologies of a 3+3 terminal off-shore DC grid are investigated without the detailed analysis of fault currents.

In summary, the researches on the characteristics of a DC short-circuit fault in the AC/DC hybrid distribution network are not comprehensive. It is necessary to study them in detail and analyse the influence of the topology on them. The rest of this paper is organised as follows. Section 2 briefly introduces the common topologies of the AC/DC hybrid distribution network. In Section 3, the characteristics of the DC short-circuit fault in a single VSC are discussed. Section 4 provides the detailed fault analysis and comparison of the three topologies introduced in Section 1 and proposes a fault current calculation method, which are validated by the simulations in MATLAB. The influence of system parameters including the fault location, fault resistance, DC capacitance, and the length of the adjacent line on the fault current characteristics is studied in Section 5. Section 6 concludes this paper.

2 Topology of AC/DC hybrid distribution network

Researches on the topology of the AC/DC hybrid distribution network are not mature now. Most of them modify the existing AC lines to build an AC/DC hybrid distribution network as an example for the design of control strategies [8, 9]. Based on the existing AC distribution network and DC distribution network topology [5], this paper summarises three possible AC/DC hybrid distribution network topologies, including tree, radial, and ring topologies as shown in Fig. 1.

The AC sides of the three VSCs are connected to the ends of the three AC distribution networks, respectively, and the AC distribution networks can be expressed by AC voltage sources. The DC network that connects the AC networks together can supply DC loads. The tree topology is the most basic three-terminal system topology [10]. It is easy to achieve fault identification and protection coordination in this network. However, when the main converter stops working, the entire DC system needs to be shut down.

The radial topology is evolved from the tree topology. The three converters form a DC bus, which is common in multi-terminal HVDC systems [10]. The cost of this topology is higher than that of the tree topology. However, the reliability of the system can be improved greatly. The remaining part can continue to exchange power, no matter which converter goes out of working. Also the radial topology is more suitable for the interconnection of different converters.

In the ring topology, which is often used as the topology of a DC micro-grid [6], converters do not need a common connection.
point. When a converter stops working, the other converters can keep working. However, compared with the tree topology and the radial topology, the ring topology has highest requirements on the protection coordination and the control strategies.

The DC short-circuit fault characteristics and the DC fault current calculation method of the three topologies will be studied next, which provide a theoretical basis for the selection of the topology and key devices of an AC/DC hybrid distribution network.

3 Analysis on VSC DC short-circuit fault characteristics

DC faults mainly include the pole-to-ground fault and short-circuit fault. The short-circuit fault is more serious, and the selection of system components is mainly based on the characteristics of the short-circuit fault [2]. Therefore, this paper focuses on the characteristics of the short-circuit fault. When a DC short-circuit fault occurs, the fault currents flowing through the insulated-gate bipolar transistors (IGBTs) increase rapidly. In order to protect the IGBTs from being destroyed, once the fault is detected, the IGBTs' internal protection devices close their control signals immediately [10, 11]. In order to simplify the analysis, let us assume that the IGBTs are closed immediately when the fault occurs. Then the converters can be seen as three-phase uncontrolled rectifiers consisting of freewheeling diodes. In addition, the lines of the DC distribution network are usually several kilometres long, so the line capacitors can be omitted, and we can use the reinforcement learning model to express the DC lines.

The equivalent circuit of a VSC after the DC short-circuit fault is shown in Fig. 2, where $U_s$, $L_s$, and $C_d$ are equivalent voltage sources and inductors of AC side. $R$ and $L$ are the equivalent resistance and inductance of the DC line, respectively. A DC short-circuit fault occurs at 0.5 s, and the simulation results are shown in Fig. 3.

Fig. 1 Topologies of the AC/DC hybrid distribution network
(a) Tree topology, (b) Radial topology, (c) Ring topology

Fig. 2 Equivalent circuit for the VSC DC short-circuit fault

Fig. 3 VSC DC short-circuit fault voltages and currents
(a) DC capacitor voltage, (b) DC Line current, (c) AC-side three-phase currents, (d) Three-phase diode currents
the DC capacitor begins to discharge, the capacitor voltage drops rapidly and the DC line current rises at the same time. During this stage, the DC line current is composed of two parts: one comes from the AC side and the other part is the DC capacitor current. Also the current from the AC side is much smaller than that from the DC capacitor current. When the DC capacitor voltage drops to 0 at 3 ms after the fault, the line inductor starts to discharge. Then a three-phase short-circuit fault occurs at the AC side, and the AC-side currents start to flow to the DC side. At this time, the DC line current is mainly determined by the AC-side currents. The rapid increase of the DC line current may destroy the freewheeling diodes, because the current flowing through the diodes reaches about 12 kA. Therefore, it is usually required that the DC circuit breakers isolate the fault line before the end of the DC capacitor discharge stage in order to protect the freewheeling diodes. Tens of milliseconds later, the system goes into a steady state, during which the DC capacitor periodically charges, and the AC-side currents keep steady.

For the AC/DC hybrid distribution network, the converters need to be connected to form a DC system. The connection structure of converters will inevitably affect the DC short-circuit fault characteristics of this network. Therefore, it is necessary to make clear the influence of system topology on the DC fault characteristics.

4 Analysis on characteristics of DC short-circuit fault in AC/DC hybrid distribution network

4.1 Analysis of fault characteristics

The DC short-circuit fault can cause a voltage decrease throughout the DC network [12]. Based on the analysis of the fault characteristics of a single VSC in Section 3, we can get the equivalent circuit of the tree topology as shown in Fig. 4.

In Fig. 4, the solid black lines represent the equivalent circuit during the DC capacitor discharge stage and the dashed black lines represent the equivalent current sources of the AC network during the AC-side current feeding stage. Due to the short lines of the AC/DC hybrid distribution network, the transmission delay caused by the reflections and refractions of the travelling wave can be neglected [13]. Therefore, it is not necessary to consider the difference of the start time of each converter's fault while calculating the fault currents. Solving the differential equations of this system, the following equations can be obtained during the capacitor discharge stage:

\[ U_{dc3} = \frac{U_{ath}}{\omega} e^{-\frac{\omega t}{3}} \sin(\alpha t + \beta) - \frac{I_{ath}}{40L_0} e^{-\frac{\omega t}{3}} \sin(\alpha t + \beta) \]

\[ i_{s0} = -\frac{I_{ath}}{\omega} e^{-\frac{\omega t}{3}} \sin(\alpha t - \beta) + \frac{U_{ath}}{40L_0} e^{-\frac{\omega t}{3}} \sin(\alpha t - \beta) \]  

Here, \( U_{ath} \) and \( I_{ath} \) are the initial values of the capacitor voltage and the DC line current before the fault, respectively, \( \delta = R_{dc2}/2L_0 \), \( \omega^2 = 1/(4L_0C) - (R_{dc2}/2L_0)^2 \), \( \alpha_0 = \sqrt{\delta^2 + \omega^2} \), \( \beta = \arctan(\omega/\delta) \). The fault currents flowing through each branches in this network are:

\[ \begin{align*}
  i_{s0} &= i_{C1} + \iota_c \\
  i_{s1} &= = -i_{C2} 
\end{align*} \]

When the capacitor voltage of each converter drops to 0, the AC-side currents start to flow to the DC side. At this time, the DC fault currents are mainly determined by the current contributed by the AC side. According to the analysis of the characteristics of the three-phase short-circuit fault of the AC system, the short-circuit current of the A phase of the AC system of the converter 3 can be expressed as follows [2]:

\[ i_{th} = i_{s0} + i_{s1} + i_{s2} \]

Then the branch currents during the fault can be calculated according to the following equation:

\[ \begin{align*}
  i_{s0} &= \iota_C + i_{C2} + i_{C3} \\
  i_{s1} &= i_{C1} + \iota_C \\
  i_{s2} &= = -\iota_C - \iota_{C2} 
\end{align*} \]

The simulation waveforms of \( i_{th} \) are shown in Fig. 5.

As shown in Fig. 5, after the fault F1 occurs, the DC capacitor \( C_1 \) starts to discharge at once. Since the lines between the converters are short, the DC capacitor \( C_2 \) discharges almost simultaneously with \( C_1 \). About 2 ms after the fault, \( \iota_C \) reaches its peak value ~27 kA. Then \( \iota_{C2} \), which is the sum of \( \iota_C \) and \( \iota_{C3} \), reaches 36 kA. At ~4 ms after the fault, the discharge of \( C_1 \) ends and its voltage equals to 0. Next \( \iota_C \) begins to flow to the DC side. The voltage of \( C_2 \) reduces to 0 at 8 ms after the fault, and \( \iota_C \) flows to the DC side. After 30 ms, the system gradually reaches a steady state, and the DC capacitor periodically charges. We can see that the peak value of \( \iota_{th} \) is mainly determined by \( \iota_C \) and \( \iota_{C2} \). The peak time of \( \iota_{th} \) is also related to the discharge characteristics of \( C_1 \) and \( C_2 \). Also the steady-state value of \( \iota_{th} \) is mainly determined by \( \iota_C \) and \( \iota_{C2} \).

For the radial topology, after the fault F1 occurs, the DC capacitor \( C_1 \) starts to discharge at once. Since the lines between the converters are short, the DC capacitor \( C_2 \) discharges almost simultaneously with \( C_1 \). About 2 ms after the fault, \( \iota_C \) reaches its peak value ~27 kA. Then \( \iota_{C2} \), which is the sum of \( \iota_C \) and \( \iota_{C3} \), reaches 36 kA. At ~4 ms after the fault, the discharge of \( C_1 \) ends and its voltage equals to 0. Next \( \iota_C \) begins to flow to the DC side. The voltage of \( C_2 \) reduces to 0 at 8 ms after the fault, and \( \iota_C \) flows to the DC side. After 30 ms, the system gradually reaches a steady state, and the DC capacitor periodically charges. We can see that the peak value of \( \iota_{th} \) is mainly determined by \( \iota_C \) and \( \iota_{C2} \). The peak time of \( \iota_{th} \) is also related to the discharge characteristics of \( C_1 \) and \( C_2 \). Also the steady-state value of \( \iota_{th} \) is mainly determined by \( \iota_C \) and \( \iota_{C2} \).
Due to the small damping of the DC system, the fault current of the converter 2 is divided into two parts: \(-i_2\) and \(i_3\). The equivalent circuit of the ring topology is shown in Fig. 7. Also the current relationship is given by

\[
\begin{align*}
-i_2 + i_3 &= i_C + i_2 \\
i_0 &= i_C + i_1 - i_2 \\
i_0 &= i_C + i_3 + i_1
\end{align*}
\]

For the ring topology, after the fault F1 as shown in Fig. 1c occurs, the fault current of the converter 2 is divided into two parts: \(-i_2\) and \(i_3\). The equivalent circuit of the ring topology is shown in Fig. 7. Also the current relationship is given by

\[
\begin{align*}
-i_2 + i_3 &= i_C + i_2 \\
i_0 &= i_C + i_1 - i_2 \\
i_0 &= i_C + i_3 + i_1
\end{align*}
\]

Based on the above analysis, we can conclude that when the other parameters of the system are determined, the topology of the DC network is the main factor determining the fault current characteristics. The topologies affect the characteristics of fault currents by changing the impedances of the fault current loops and the number of current branches fed into each line. The larger the impedance of the fault current loop, the smaller the peak value of the corresponding fault current. Also, the more current branches that feed into the line are, the larger the peak values of the line currents are. There is only one line withstanding two current branches in the tree topology. In the radial topology, only the end of the faulty line close to the common connection point needs to withstand the fault currents contributed by the non-faulty converters. The faulty line of the ring topology must be able to withstand the currents from all the other converters.

### 4.2 Calculation method of transient fault current

Due to the small damping of the DC system, the fault current increases rapidly after the fault. If the fault is not isolated in time, the IGBTs in the converters will be immediately blocked, causing the entire system to stop working. At the same time, other devices in the system will be seriously affected. Therefore, calculating the transient values at some characteristic points of the fault currents is crucial to the safe operation of the system. Based on the analysis in Section 4.1, this paper proposed a calculation method of the peak values, peak times, and the rising rates of the fault currents.

Since the DC currents during the normal operation of AC/DC hybrid distribution network are much smaller than the DC fault currents, the calculation of the transient characteristic values of the DC fault currents can be simplified by neglecting the first term of (2); then

\[
i_0 = \frac{U_0}{40L_2a}e^{-\frac{a}{\omega}}\sin \alpha \omega t \leq \frac{U_0}{40L_2a}
\]

\[
\frac{di_0}{dt} = \frac{U_0}{40L_2a}(\omega e^{-\frac{a}{\omega}}\cos \alpha \omega t - \delta e^{-\frac{a}{\omega}}\sin \alpha \omega t)
\]

\[
=\frac{U_0}{40L_2a}\sqrt{\omega^2 + \frac{\delta^2}{\omega^2}}(\cos \alpha \omega t + \frac{\delta}{\omega^2}\sin \alpha \omega (t + \gamma))
\]

Then, let \(1 = \alpha\); we can obtain the end time of the capacitor discharge stage as

\[
t_1 = \frac{\pi - \alpha}{\omega}
\]

Here, \(\alpha = \arctan[(U_{dcb}C\sin \beta) / (U_{dcb}C\cos \beta - I_0)]\). Since the difference between the end time of the capacitor discharge stage and the peak time of the fault current is small, the latter can be estimated by the former and calculated using (11). Then, we can obtain the characteristic values of the fault currents from (9) to (11).

For DC lines with several current branches feeding, the following inequality can be obtained:

\[
i_{t0} \leq i_{peak} \leq i_{Cpeak} + i_{2peak}
\]

(12)

\[
f_{peak} = \min \left(\frac{di_{Cpeak}}{dt}, \frac{di_{2peak}}{dt}\right)
\]

(13)

\[
\frac{di_0}{dt} \leq \max \left(\frac{di_{Cpeak}}{dt}, \frac{di_{2peak}}{dt}\right)
\]

(14)

These estimations may exaggerate the severity of the fault. However, it is acceptable for the project applications and can improve the efficiency of the calculation greatly.

### 4.3 Simulation analysis

Simulation models of the tree, radial, and ring topology are built in MATLAB. The fault characteristics of them are studied and compared. The peak values and peak times of fault currents are shown in Fig. 8. Here, VSC1s, VSC2s, and VSC3s represent the fault currents at the starting point of the DC line of each converter. VSC1e, VSC2e, and VSC3e represent the fault currents at the end point of the DC line of each converter. As shown in Fig. 8, the relationship between the fault current of each line is consistent with the above analysis. The impedance of the DC capacitor discharge loop in the radial topology is higher, so it has smaller peak values and longer peak times. Overall, the radial topology has the lowest requirements on the protection devices without taking the fault current limiting measures into consideration. Also the ring topology has the most restricted requirements.

According to (8)–(10), the peak values, the rising rates, and the peak times of fault currents after the fault of the tree topology are calculated and compared with the simulation results as shown in Table 1. As shown in Table 1, the calculation results of the proposed method and the simulation results are almost the same. The difference between them is acceptable for the protection design.
The influence of system parameters on fault characteristics is studied in the tree topology. The converter 1 controls the DC voltage, and converters 2 and 3 control the active power. The simulation parameters are shown in Table 2.

When a DC short-circuit fault occurs, the fault currents will be affected by the fault distances, fault resistances, DC capacitors, and the lengths of the adjacent lines. We take the fault current of the faulty line as an example to study the fault current characteristics with different system parameters.

### 5.1 Fault distances

When there is a fault on the line between converters 1 and 3, the distances \( d \) between the fault point and converter 1 are 100, 300, 500, and 700 m. The fault current \( i_10 \) is shown in Fig. 9.

The change of the distance between the fault point and the converter 1 leads to the change of the equivalent resistances and inductances of the faulty line. During the capacitor discharge stage, as the fault distance increases, the impedance of the capacitor discharge loop increases, resulting in a decrease of the peak value of the capacitor discharge current. Since \( i_{10} \) is the sum of the fault current of converters 1 and 2, the peak value of \( i_{10} \) decreases accordingly. After the system reaches a steady state, \( i_{10} \) is mainly determined by the amplitude and frequency of the AC sources and the system damping. An increase in fault distance results in a steady-state current decrease, but the effect is less noticeable due to the smaller line resistance and inductance compared to the system impedance.

### 5.2 Fault resistances

Setting the fault distance to 500 m, the fault resistances are 0.001, 0.01, 0.1, and 1 Ω, respectively. The fault current \( i_{10} \) is shown in Fig. 10.

As the fault resistance increases, the capacitor discharge loop becomes overdamped, and the DC voltage will no longer drop to 0. The capacitor discharge current will decrease, resulting in the decrease of peak values of \( i_{10} \) and the change of state of oscillation. When the fault resistance increases from 0.1 to 1 Ω, we can see that the damping characteristics of the discharge circuit have been obviously changed, and the peak value of the fault current decreases sharply. After the end of the capacitor discharge stage, the amplitude of \( i_{10} \) will also have a reduction.
does not affect the magnitude of peak time is slightly delayed. In addition, the increase of the length of adjacent lines will also increase the impedance of the AC-side current feeding loop, so as to reduce the amplitude of the AC-side feeding current. The AC-side feeding current is delayed due to the increase of the capacitor discharge time, but the amplitude of the steady-state current is not affected by the DC capacitor.

5.4 Lengths of adjacent lines

Set the fault distance to 500 m, the fault resistance to 0.001 Ω, and the size of the DC capacitor to 4800 μF. Then, the lengths of the lines between the converters 1 and 2 are 100, 500, 1000, and 1500 m, respectively. The fault current \( i_{\text{fa}} \) is shown in Fig. 12.

The change of the line length between the converters 1 and 2 does not affect the magnitude of \( i_{\text{fa}} \), but it will affect the resistance and the inductance of the DC capacitor discharge loop of the converter 2. The shorter the length of the adjacent line, the greater the peak value of the DC capacitor discharge current, and the faster the discharging speed. So when the peak value of \( i_{\text{fa}} \) increases, the peak time is slightly delayed. In addition, the increase of the length of the adjacent line will also increase the impedance of the AC-side current feeding loop, so as to reduce the amplitude of the AC-side feeding current.

In summary, the fault distance, fault resistance, DC capacitor, and the length of the adjacent line will affect the fault current flowing through the faulty line in the AC/DC distribution network. All the parameters should be considered while studying the fault characteristics.

6 Conclusions

In this paper, the characteristics of the DC short-circuit fault in the AC/DC hybrid distribution network with different topologies are analysed. The equivalent circuit of the system is proposed. The analytical expressions of fault currents are deduced. Besides, a method to calculate the characteristic values of the fault currents is studied and verified, and the influence of the system parameters on the characteristics of the fault current is analysed thoroughly. The conclusions are as follows:

(i) After a DC short-circuit fault occurs in the AC/DC hybrid distribution network, the system can be seen as a simple system consisting of DC capacitors, AC sources, and equivalent impedances. The fault process can be divided into the DC capacitor discharge stage and the AC-side current feeding stage.

(ii) In an AC/DC hybrid distribution network, the topologies of DC network influence the characteristics of the fault current by changing the capacitor discharge loop impedance and the number of the current feeding branches. The radial topology has the lowest requirements on the breaking time and breaking capacity of the DC circuit breaker without taking other current limiting and protection measures into consideration. The tree topology and the ring topology have the higher requirements. Therefore, when selecting the topology of the AC/DC hybrid distribution network, the fault characteristics of the system should be considered.

(iii) The current flowing through the faulty line is affected by parameters such as fault distance, fault resistance, DC capacitor, and the length of adjacent lines. The AC/DC hybrid distribution network should be designed considering these factors.

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8 References

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