Direct current distribution network protection scheme based on inductive current limiting

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Abstract. Converter blocking in the case of pole-to-pole short circuit of the direct current (DC) distribution network can cause large-scale power outage and slow system recovery. Given this issue, a scheme of short circuit protection between poles of the DC distribution network based on the cooperation of fault current limiting module and DC circuit breaker is proposed in this paper. According to the inductive current limiting topology, the transient characteristics of the bridge arm current and the fault current on the DC side of the converter are analyzed, and the theoretical calculation method and selection principle of the current limiting inductor parameters are given. The proposed protection scheme can realize the fault ride-through of the converter during the pole-to-pole short circuit, reduce the scope of power outage and quickly restore the system. The simulation results under the PSCAD/EMTDC environment verify the correctness and feasibility of the protection scheme.

1. Introduction
The DC distribution network has attracted much attention from academia and industry due to its easy access to distributed power sources, low line loss, and high reliability of power supply[1,2]. However, the fault current of pole-to-pole short circuit in the DC distribution network has a large component and a fast rise rate[3]. Under its own protection, the IGBT in the converter sub-module can be blocked within 1ms of the fault. Nevertheless, the fault current could still damage the anti-parallel diode. This places extremely high requirements on the operating speed and breaking capacity of the DC circuit breaker (DCCB). At present, the medium voltage DCCB with large capacity and fast cut-off capability is still not enough for engineering application[4]. Therefore, the use of fault current limiting measures to suppress transient fault current components and achieve effective fault isolation is of great practical significance to improve the power supply reliability of the DC distribution network.

Existing fault current limiting measures mainly include converter valve topology transformation, installation of fault current limiting modules or devices. Traditional two-level and three-level voltage source converters and half-bridge modular multilevel converters cannot clear fault currents. For this reason, researchers have successively proposed new topological structures[5-6]. Device-based current limiting was studied in [7-8], and the function of superconducting fault current limiter(SFCL) in the HVDC transmission line and DCCB was discussed. However, the current limiting parameter selection method proposed above does not consider the overcurrent capacity of the converter’s IGBT and the reverse shunt diode during the fault process.
In this paper, general principles and theoretical calculation methods for the selection of current-limiting module parameters are provided regarding inductive current-limiting modules based on the fault current analysis. Besides, a specific scheme for short-circuit protection between poles is designed. The proposed protection scheme can reduce the range of system power outage when an inter-electrode short-circuit fault occurs on the DC side, improve the system recovery speed, and lower the requirements on the breaking time and cut-off capacity of the DCCB.

2. DC distribution network topology
The DC distribution network in the paper adopts the double-ended power supply topology presented in Figure 1. The alternating current (AC) side and the DC side are connected through an AC transformer and a modular multilevel converter (MMC). The short-circuit fault studied in this paper is a short-circuit fault between the poles of the medium voltage DC side, and the AC transformer adopts the method of grounding the neutral point of the valve side through the resistance. The converter station at one end is in constant voltage mode, and the other end is in constant power mode.

3. Protection method based on inductive current-limiting module

3.1. Inductive current-limiting module
The inductive current-limiting module adopts a parallel structure of a current-limiting inductor and a metal-oxide arrester (MOA), and is installed on the DC outlet side of the converter, as illustrated in Figure 2.

When the system is operating normally, the DC current flows through the current-limiting inductor, no voltage drop is generated, and the steady-state loss is small. When the system fails, the DC current changes suddenly, and a corresponding voltage drop occurs across the inductor. At this time, the MOA connected in parallel with it absorbs circuit energy, enabling it to effectively protect the inductor from damage caused by overvoltage. Under the action of the current-limiting inductance, the fault current rises slowly, and the peak current decreases.

3.2. Parameter selection
3.2.1. Principle of inductance value.
Considering the converter, line protection requirements, and the main performance parameters of DCCB, the parameter value constraints of the inductive current limiter are:

\[
\begin{align*}
\text{max}(dI_{\text{dc}}) &< dI_{\text{CB max}} \\
\text{max}(I_{\text{dc}}) &< k_1 I_{\text{CB max}} \\
\text{max}(I_{\text{inj}}) &< k_2 I_{\text{inj}} \\
\text{max}(I_{\text{diode}}) &< k_3 I_{\text{diode}}
\end{align*}
\] (1)
where, \( \max(dI_{dc}) \) represents the maximum rate of rising of fault current on the DC side; \( dI_{CB\text{max}} \) denotes the maximum current change rate that the DCCB can withstand; \( \max(I_{dc}) \) refers to the maximum value of DC line fault current; \( I_{CB\text{max}} \) is the maximum breaking current of the DCCB; \( k_1 \) is the reliability coefficient, 0.7~0.9; \( \max(I_{IGBT}) \) and \( \max(I_{diode}) \) indicate the maximum fault currents flowing through the converter’s IGBT and the anti-parallel diode before the DCCB operates, respectively; \( I_{n1} \) and \( I_{n2} \) are the rated current of IGBT and diode, respectively. The maximum steady-state current that the two devices can withstand is generally twice the rated current. Considering a certain margin, \( k_2 \) and \( k_3 \) can be set as 1.7~1.9.

### 3.2.2. Parameter calculation.

When a short-circuit fault occurs on the DC side of the half-bridge MMC, the capacitors of the sub-modules of each bridge arm of the converter are quickly discharged to the short-circuit point through the IGBT. Simultaneously, the AC side injects a short-circuit current to the fault point on the DC side through an anti-parallel diode. Among them, the short-circuit current is mainly determined by the discharge current of the sub-module capacitor in the input state. A schematic diagram of the discharge path of a single-phase bridge arm sub-module is illustrated in Figure 3.

![Figure 3. Discharge path of single-phase bridge arm submodule.](image)

Due to the low damping characteristics of the DC distribution network, the capacitor discharge phase of the pole-to-pole short circuit of the DC distribution network generally satisfies \( R < 2\sqrt{L/C} \). It is an underdamped process. The fault current equation and the current peak time are:

\[
I_{dc}(t) = e^{-\frac{t}{\tau}}[\frac{U_c(0)}{\omega L}\sin \omega t - \frac{I_{n1}(0)\omega h}{\omega} \sin(\omega t - \beta)]
\]

(2)

\[
t_{dpeak} = \frac{\beta}{\omega}
\]

(3)

where, \( U_c(0) \) and \( I_{n1}(0) \) are the capacitor voltage and DC current of the bridge arm at the time of the fault, respectively; \( \tau = 2L/R \); \( \beta = \arctan(\omega t) \); \( \omega_h = \sqrt{1/(LC_{eq})} \); \( \omega = \sqrt{\omega_h^2 - (1/\tau)^2} \); \( R \), \( L \), and \( C_{eq} \) denote the equivalent discharge loop resistance, inductance, and capacitance of the three-phase bridge arm, respectively; \( L = 2L_{arm}/3 + L_F \); \( C_{eq} = 6C_0/n \); \( C_0 \) represents the capacitance value of the sub-module; \( n \) indicates the number of single-phase bridge arm sub-modules. By performing derivation of the fault current equation, the expression of the differential value of the DC side fault current is obtained as:

\[
dI_{dc} = e^{-\frac{t}{\tau}}[-\frac{U_c(0)\omega h}{\omega L} \sin(\omega t - \beta) + \frac{I_{n1}(0)\omega h^2}{\omega} \sin(\omega t - 2\beta)]
\]

(4)

Since the fault current curve in the capacitor discharge stage is a convex function, the current differential takes the maximum value at the initial fault \( t = 0^+ \):

\[
\max(dI_{dc}) = \left. \frac{dI_{dc}(t)}{dt} \right|_{t=0^+} = \frac{U_c(0)\omega h}{\omega L} \sin \beta - \frac{I_{n1}(0)\omega h^2}{\omega} \sin 2\beta = \frac{U_c(0) - I_{n1}(0)R}{L}
\]

(5)
Considering the most serious situation, namely the DC bus failure, the equivalent resistance $R$ of the discharge circuit is very small at this time [9]; it can be approximated that $\omega=\omega_0$, $\beta=\pi/2$. Thus, the current peak time and the current peak value can be approximated as:

$$t_{\text{dc peak}} = \frac{\pi}{2} \sqrt{L C_{\text{eq}}}$$

(6)

$$I_{\text{dc peak}} = \sqrt{\frac{C_{\text{eq}} U_c^2(0) + I_c^2(0)}{L}}$$

(7)

It can be observed from the capacitor discharge path in Figure 3 that the capacitors of the sub-modules in the input state discharge the fault points through the IGBT; the fault current of the sub-module in the cut-off state is injected into the short-circuit point through the anti-parallel diode. Therefore, in the capacitor discharge phase, the current of the IGBT ($I_{\text{IGBT}}$) and the fault current flowing through the diode ($I_{\text{diode}}$) are the same. The peak value and peak time of the fault current are in the same form as Equations (6) - (7). $I_c(0)$ indicates the single-phase bridge arm current at the time of failure; $L$ and $C_{\text{eq}}$ represent the equivalent discharge loop inductance and capacitance of the single-phase bridge arm, respectively; $L=2L_{\text{arm}}+L_F$, $C_{\text{eq}}=2C_0/n$.

The maximum value of DC line fault current $\max(I_{\text{dc}})$ before the DCCB operates is related to the circuit breaker operating time (fault duration) $t_{\text{break}}$, as well as the maximum value of the fault current $\max(I_{\text{IGBT}})$ and $\max(I_{\text{diode}})$ flowing through the converter’s IGBT and the anti-parallel diode. If the DCCB is opened before the current peak time, the maximum value is taken as the fault current value at $t_{\text{break}}$, otherwise, the current peak value is:

$$\max(I) = \begin{cases} 
I_{\text{peak}} & t_{\text{break}} > t_{\text{peak}} \\
I(t) & t_{\text{break}} \leq t_{\text{peak}} 
\end{cases}$$

(8)

Equation (8) is applicable to the DC side, IGBT, diode fault current $I_{\text{dc}}$, $I_{\text{IGBT}}$, and $I_{\text{diode}}$.

### 3.3. Protection scheme

The above protection principle can determine the corresponding inductance parameters. The specific process of protection scheme based on the inductive current-limiting module is exhibited in Figure 4.

![Inductive current-limiting protection scheme](image)

Figure 4. Inductive current-limiting protection scheme.
1) Fault determination: When a short-circuit fault occurs between the poles of the DC line, the submodule capacitor discharges quickly, and the voltage on the DC side drops rapidly. This configures the DC low-voltage over-current protection, and its action criterion is:

\[
\begin{align*}
|U_{\text{pos}} - U_{\text{neg}}| < U_{\text{set}} \\
|I_{\text{dcp}}| > I_{\text{set}} \\
|I_{\text{dcn}}| > I_{\text{set}}
\end{align*}
\]

where, \(U_{\text{pos}}\) and \(U_{\text{neg}}\) are the positive and negative voltages on the DC outlet side, respectively; \(I_{\text{dcp}}\) and \(I_{\text{dcn}}\) represent the positive and negative currents of the DC side, respectively; voltage action threshold is \(U_{\text{set}} = k_{\text{set}}U^*\); current operating threshold is \(I_{\text{set}} = k_{\text{set}}I^*\); \(U^*\) and \(I^*\) denote the steady-state value of the DC voltage and current of the system, respectively, with the value of 20kV and 0.5kA; \(k_{\text{set}}\) and \(k_{\text{set}}\) are 0.75 and 2, respectively.

2) The DCCB trips: Since the half-bridge MMC does not have the ability to clear fault currents, to ensure that the converter does not lock during a fault, it is necessary to open the DCCB when the fault current flowing through the converter’s IGBT, anti-parallel diode, and DC side reaches the threshold, so as to cut off the capacitor discharge circuit. The inductive current-limiting module significantly slows down the rising speed of the fault current and reduces the requirements for the breaking time and capacity of the DCCB.

3) Fault recovery: After the fault is cleared, the DCCB is closed to restore the power transmission of the system.

4. Simulation

4.1. Simulation parameter

| Type          | Parameter                        | Value   | Parameter                        | Value   |
|---------------|----------------------------------|---------|----------------------------------|---------|
| AC Power System | AC Power Grid Line Voltage/kV     | 110     | Converter Submodule Capacitance/mF | 2       |
|               | Rated Power/MW                   | 10      | IGBT Rated Current /kA           | 1.8     |
| DC Power System | Cable Resistance/(Ω/km)          | 0.047   | Diode Rated Current /kA          | 1.6     |
|               | Cable Inductance/(mH/km)         | 0.53    | IGCT Voltage Limit/kV            | 5.5     |
|               | Line Length/km                   | 15      | Breaking Current/kA              | 10      |
| Converter     | Number of single-phase bridge arm modules | 40     | Hybrid Medium-Voltage DCCB       | 4       |
|               | Bridge Arm Inductance/mH         | 5       | Maximum Current Change Rated/(kA/ms) | 4       |

4.2. Simulation analysis of protection method based on inductive current-limiting module

According to the analysis in section 3.2.2, the maximum value of the fault circuit of the converter’s IGBT, diode, and DC side is related to the fault duration tbreak. Therefore, the parameters are substituted into the calculation for the inductance value range with 1ms as the time interval. The range of inductance parameters under different fault durations is presented in Table 2.

As revealed from the data in the table, the inductance parameter value increases with the increase in the fault duration. The inductance parameter range remains unchanged when the fault duration exceeds 8ms. The reason is that the action time of the DCCB is longer than the peak current time, and the peak value of the fault current flowing through the IGBT, the diode, and the DC side does not exceed the threshold. Considering factors such as current-limiting reactor investment cost and power loss, it is recommended to take the critical value of the inductance parameter range. Furthermore, 4ms fault duration and 14mH current-limiting inductance are selected based on system parameters to provide sufficient fault transient information and ensure the balance of reliability and rapidity.
Table 2. Value range of inductance parameter.

| Duration of Fault/ms | Range of Inductance Parameter | Duration of Fault/ms | Range of Inductance Parameter |
|----------------------|-------------------------------|----------------------|-------------------------------|
| 1                    | Without Inductance            | 5                    | L>18.44mH                     |
| 2                    | L>3.1mH                       | 6                    | L>21.93mH                     |
| 3                    | L>8.81mH                      | 7                    | L>24.47mH                     |
| 4                    | L>13.91mH                     | ≥8                   | L>25.64mH                     |

Besides, a comparison test was conducted with no current-limiting inductor added and a 7mH current-limiting inductor added as the control group. The DC bus has an inter-electrode short circuit at t=2s. The simulation waveforms of DC side current and AC side voltage and current are illustrated in Figures 5-6. Since the rated current of the IGBT is higher than that of the diode, the fault current only needs to satisfy the diode constraint. The diode current peak value for each inductance for a 4ms fault duration is provided in Table 3.

Table 3. Peak diode current under different inductances.

| L/mH     | 0  | 2  | 4  | 6  | 8  |
|----------|----|----|----|----|----|
| I_{diode}/kA | 5.90 | 5.07 | 4.55 | 3.95 | 3.52 |

It can be observed from Figure 5 that the fault current rises fast and the amplitude is high without adding the current-limiting inductance module, and quickly breaks through the maximum breaking current of the DCCB; moreover, the DCCB could not be opened, and the diode peak current reached 5.90kA and was destroyed. Although the current-limiting inductance of 7mH has met the breaking requirements of the DCCB, the peak value of the diode current is still too large (Table 3). When a 14mH current-limiting inductor is added to the DC outlet side of the converter, the fault current on the DC side is much lower than the maximum breaking current. Simultaneously, the diode peak current is also less than the setting threshold. As a result, the converter is not blocked when a fault occurs, the fault ride-through capability of the converter in the case of a pole-to-pole short circuit is improved, and the correctness and feasibility of the proposed inductance value principle and protection scheme are verified. According to the AC current and voltage waveforms under different inductance conditions, as the current-limiting inductance value increases, the AC side fault current amplitude decreases, and the voltage drop problem is also improved. Therefore, the current-limiting inductor also contributes to limiting the amplitude of the fault current on the AC side and maintaining the voltage on the AC side, as presented in Figures 6.

5. Conclusions

Aiming at the large-scale power outage and slow system recovery problems caused by converter blocking in the case of pole-to-pole short circuit in DC distribution network, based on the principle of...
current-limiting related parameters and theoretical calculation methods from the analysis of the transient characteristics of DC faults, a pole-to-pole short circuit protection scheme is proposed for inductive fault current-limiting modules. The following conclusions are drawn:

1) The protection method based on inductive current-limiting module uses inductance to slow down the rising speed of the current and reduce the action speed and breaking capacity of the DCCB;

2) When a short circuit fault occurs between the DC side of the system, this proposed method can limit the AC and DC side fault currents, maintain the AC side voltage, ensure that the converter is not blocked, reduce the power outage range, and accelerate the system recovery speed;

3) The proposed protection method can provide a reference for the value of current-limiting parameters according to specific system parameters and has certain guiding significance for engineering applications.

Therefore, this protection scheme is verified to provide good protective effects for the DC distribution network, and can be applied to protect electric equipment from DC fault.

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