Protection Scheme of Multi-terminal Flexible DC Distribution Network Based on Current-Limiting Inductor Voltage

Xin Shangguan, Wenping Qin, Cheng Wang and Yuan Niu

College of Electrical and Power Engineering, Taiyuan University of Technology, Shanxi, China

No.79 West Yingze Street, Taiyuan, 030024, Shanxin Province, P.R.China

Mobile: +86-13468281667

E-mail: 1183129090@qq.com

Abstract. The rapid development of power electronic devices has promoted the rapid development of multi-terminal flexible DC distribution networks, indicating the direction of DC technology and urban power distribution systems. However, there are several technical problems in multi-terminal flexible DC distribution network that still need to be solved. In relay protection, the main difficulty faced by DC distribution network is the rapid and reliable identification of DC faults. This paper proposes a multi-terminal flexible DC distribution network protection scheme based on current-limiting inductor. First, the system configuration of the multi-terminal flexible DC distribution network is introduced. Then, the DC-side fault characteristic of the flexible DC distribution network are analysed. Based on this, a protection scheme based on current-limiting inductor voltage is proposed. Next, a complete protection scheme is designed. Finally, the proposed protection scheme is verified by real time digital simulator (RTDS). The simulation results show that the scheme is not affected by the fault resistance and fault distance.

1. The first section in your paper

In recent years, with the development of power electronics technology and DC energy storage devices, the power supply and load in the power system have changed a lot, and the proportion of distributed sources in power energy is increasing [1]. The DC distribution network has obvious advantages, for example, large power transmission capacity, convenient distributed energy access, low line loss, high reliability and high power supply quality [2-4].

At present, the DC side fault protection scheme for flexible DC systems has been discussed in the literature [5-10]. The principle of “handshake method” is proposed to identify the fault line [5], which can accurately identify the DC side fault line by the action of the AC side circuit breaker on the premise that the DC circuit breaker is difficult to develop. However, this protection scheme needs to disconnect all AC circuit breakers, resulting in short-time power failure in non-faulty areas. Wu [6] proposes an inverse time-limited current variance protection scheme to identify DC faults and determine the severity of faults based on two-terminal DC power distribution system. However, the scheme cannot identify faults inside and outside the area for multi-terminal flexible DC distribution network. ABB and SIMENS proposed traveling wave protection and differential undervoltage protection as the main protection for HVDC transmission system, and differential protection as the protection scheme for backup protection [7-8], but the method is difficult to capture the wave head and
have a large error due to short line of DC distribution network. Li [9] uses boundary elements to identify faults within and outside the area based on transient energy methods, but this solution cannot perform fault selection. The curvature algorithm is used to characterize the distortion of the current waveform [10], and the curvature change of the current is used to identify the fault. In addition, most of the above documents cannot identify DC bus faults and the threshold tuning is mostly obtained through simulation experiments, which lacks theoretical analysis and calculation.

2. System configuration
This paper takes multi-terminal DC distribution system as the research object. The system mainly includes key devices such as inverter, DC circuit breaker and DC line. The inverter uses two-level voltage source converter (VSC). The system structure is shown in Figure 1. F1~F4 are fault locations. The current-limiting inductor is installed between the DC breaker and the DC transmission line. The master-slave control mode is adopted in this paper. VSC1 adopts constant DC voltage control to support the voltage of the whole DC system as the balance node of the system, VSC2-VSC4 adopts constant power control as the power node of the system [11].

3. Analysis of transient characteristics of flexible DC distribution network
The types of faults on the DC side of the flexible DC distribution network mainly include pole-to-pole fault and pole-to-ground fault. Among these, pole-to-ground fault is the most common, and pole-to-pole fault is the most serious.
3.1. Pole-to-pole fault

The equivalent circuit of the bipolar short-circuit fault on the DC side is shown in Figure 2. Assume that the capacitor voltage and inductor current are \( u_c(0) \) and \( i_L(0) \) at the moment of fault occurrence. The frequency domain expression of the process is shown in equation (1).

\[
i_i(s) = \left[ \frac{u_c(0)}{L} + i_L(0)s \right] s^2 + \frac{R}{L} s + \frac{1}{LC} = 0
\]

(1)

In general, the fault resistance of the pole-to-pole fault is 0, and the resistance of the DC line is also small, and the fault loop is under-damped, the time domain solution of the DC side line current \( i_L \) and voltage \( U_{dc} \) is:

\[
i_L(t) = \frac{u_c(0)}{\alpha_j L} e^{-\alpha_j t} \sin(\alpha_j t) - \frac{i_L(0)}{\alpha_j} e^{-\alpha_j t} \sin(\alpha_j t - \beta)
\]

(2)

\[
U_{dc}(t) = -\frac{1}{C} \int i_L(t) dt = \frac{u_c(0)}{\alpha_j} e^{-\alpha_j t} \sin(\alpha_j t + \beta) - \frac{i_L(0)}{\alpha_j} e^{-\alpha_j t} \sin(\alpha_j t)
\]

(3)

In the formula (2) and (3):

\[
\alpha = \sqrt{\frac{R}{LC}}, \beta = \arctan\left(\frac{\alpha_j}{\alpha}\right)
\]

4.2. Pole-to-ground fault

When a pole-to-ground fault occurs on the DC side, the fault current flow path is shown in Figure 3. When the circuit is in an over-damped discharge state, the time domain expression is:

\[
i_i(t) = \frac{u_c(0)}{\alpha_j L} e^{-\alpha_j t} \sin(\alpha_j t) + \frac{i_L(0)}{\alpha_j} \left(\frac{e^{-\alpha_j t} - e^{-\alpha_j t}}{p_2 - p_1}\right)
\]

(4)

\[
U_p(t) = -\frac{1}{C} \int i_i(t) dt = \frac{u_c(0)}{\alpha_j} e^{-\alpha_j t} \sin(\alpha_j t) + \frac{i_L(0)}{\alpha_j} \left(\frac{e^{-\alpha_j t} - e^{-\alpha_j t}}{p_2 - p_1}\right)
\]

(5)

In the formula (4) and (5):

\[
R = R_{eq} + R_f, L = L_{eq}, C = C_{eq}, \alpha = \frac{R}{2L}, \beta = \arctan\left(\frac{\alpha_j}{\alpha}\right)
\]

4. Protection scheme

Based on the above analysis, this paper proposes a multi-terminal flexible DC distribution network protection scheme based on current-limiting inductor voltage. The scheme includes five parts: fault start, fault detection, fault identification, fault pole selection and DC bus fault criterion.

4.1. Fault start criterion

It can be seen from the analysis in the third section that after a fault occurs on the DC side, the voltage at the moment of the fault decreases and the current increases. Therefore, the fault start component is formed by the change amount of the DC voltage and current after the fault, then the criterion of fault start is shown in formula (6).

\[
\frac{du}{dt} > 0.1U_n, \frac{di}{dt} > 0.1I_n
\]

(6)

Where: \( u, i \) represents the DC line voltage and current of the positive or negative pole, \( U_n, I_n \) represent the rated values of the DC voltage and current.

4.2. Fault detection criterion

When the system is disturbed or interfered, it may cause the fault start criterion acts, therefore, the fault detection component is constructed according to the low voltage and overcurrent protection. The fault detection criterion is shown in formula (7).

\[
U_{dc} < 0.8U_n \cap i > 1.5I_n
\]

(7)
4.3. Fault identification criterion

As shown in Figure 4, taking the VSC1 as an example, each line outlet is equipped with a protection device and a current-limiting inductor. The direction of positive line sets as the bus pointing to the line, and the positive direction of the negative line sets as the line pointing to the bus. Therefore, when the fault occurs in the positive direction, the fault moment has $\frac{di}{dt} > 0$, as shown in formula (8).

$$U_{L12P} = L \frac{di}{dt} > 0$$ (8)

Conversely, when a positive ground fault occurs on the back side of the protection device 11P, the fault current increases inversely, as shown in formula (9).

$$U_{L12P} = L \frac{di}{dt} < 0$$ (9)

In the formula: $UL12P$ is the voltage across the current-limiting inductor of the positive line.

Therefore, the protection criteria for the fault in the positive direction of the protection device $m$ is shown as formula (10).

$$R_{\text{set}} = \begin{cases} 1, & U_{\text{set}} > U_{\text{set}} \\ 0, & U_{\text{set}} < -U_{\text{set}} \end{cases}$$ (10)

Where: $m$ is the number of the DC breaker, $m=12, 21...14$; $t$ is the positive and negative poles of the DC breaker, $t=P, N, P$ for the positive pole, $N$ for the negative pole. $U_{\text{set}}$ is equivalent to the current-limiting inductor during normal operation of the line.

The fault identification criteria as shown in formula (11).

$$S_k = \begin{cases} 1, & R_{\text{set}} \cdot R_{\text{set}} = 1 \\ 0, & R_{\text{set}} \cdot R_{\text{set}} = 1 \end{cases}$$ (11)

Where: $n$ represents the DC breaker at the opposite end of the line where $m$ is located.

4.4. Fault pole selection criterion

$$R_{\text{set}} \cdot R_{\text{set}} = 1$$

4.5. DC bus fault criterion

When the DC line fails, the DC circuit breaker at both sides of the line can be cut off to remove the fault without affecting the normal power transmission of the inverter. When the DC bus fault, the amplitude of the positive or negative voltage connected to the bus will decrease, as shown in (13).

$$U_{L12P} = L \frac{di}{dt} < 0 \cup U_{L12N} = L \frac{di}{dt} < 0$$ (13)

The DC bus fault criterion as shown in formula (14).

$$S_k = \begin{cases} 1, & R_{\text{set}} \cdot R_{\text{set}} = 0 \\ 0, & R_{\text{set}} \cdot R_{\text{set}} = 1 \end{cases}$$ (14)

Where: $k$ and $m$ are DC breakers on the bus side of the DC line directly connected to the same bus.

4.6. Flow diagram of protection strategy

The flow chart of the multi-terminal flexible DC distribution network protection scheme designed in this paper is shown in Figure 5.

5. Simulation

In this paper, the four-terminal flexible DC distribution network topology shown in Figure 1 is built in RTDS. The simulation parameters of the system are shown in Table 1. The DC line adopts the RL
equivalent model, and the parameters of the current-limiting inductor of each DC line are designed by the scheme proposed in [12-13], and the sampling frequency is 20 kHz. The protection criterion threshold $U_{set}$ is 0.6 kV.

| System parameters | Value | System parameters | Value | System parameters | Value |
|-------------------|-------|-------------------|-------|-------------------|-------|
| Rated DC voltage/kV | ±10   | Rated AC voltage/kV | 110   | Line 1/km | 12 |
| Line resistance/(Ω/km) | 0.121 | Line inductor/(mH/km) | 0.97 | Line 3/km | 10 |
| VSC 1/kV | ±10   | VSC 2/MW | 4    | VSC 3/MW | 4 |
| VSC 4/MW | -5    | DC capacity/μF | 4800 |
| Current-limiting inductor/mH | 5 |

Table 1. Parameters of system simulation.

5.1. Zone and outer fault simulation

5.1.1. Positive pole-to-ground fault of DC line 1. At 1 s, the positive pole-to-ground fault F1 is applied to the DC line Line1, and the simulation result is shown in Figure 6. Among them, Figure (a) is the characteristic curve of each current-limiting inductor voltage. It can be seen from the figure that when a positive pole-to-ground fault occurs, the current-limiting inductor voltage at both sides of the Line1 positive line is greater than the threshold value and the DC breaker acts, as shown in the figure (b), the current-limiting inductor voltage at both sides of the non-faulty line changes in the opposite direction, and the circuit breaker does not operate.

![Figure 6. Simulation waveform of positive pole-to-earth fault of DC line1.](image)

5.1.2. Pole-to-pole fault of DC line 4. At 1 s, a pole-to-pole fault F3 is applied at the midpoint of the DC line Line4, and the simulation result is shown in Figure 7. It can be seen that when a pole-to-fault occurs, the current-limiting inductor voltage at both sides of Line 4 positive and negative lines is greater than the threshold value, and the DC breaker acts as shown in Figure (b).

![Figure 7. Simulation waveform of pole-to-pole fault of DC line4](image)

5.1.3. Pole-to-pole fault of DC Bus 2. At 1 s, a pole-to-pole fault F4 is applied to the DC bus Bus2, and the simulation result is shown in Figure 8. It can be seen from the figure that when a DC bus fault
occurs, the current-limiting inductor voltage at both sides of the Line 2 and 3 positive and negative lines is less than the threshold. As shown in Figure (b), DC breakers on the bus side of DC line that connects to the bus operate, and the remaining circuit breakers do not operate.

5.2. Protection action performance

5.2.1. The effect of the fault resistance on the protection scheme. The maximum resistance of the DC distribution network is generally ten ohms. Table 2 shows the current-limiting inductor voltage at both ends of the DC line and fault detection under various fault resistances of 0, 1, 10, and 20 Ω for various fault types of DC lines. For pole-to-ground fault and pole-to-pole fault, the voltage of the current-limiting inductor at both ends of the line is detected. It can be seen from Table 2 that as the resistance of the fault resistance increases, the resistance of the capacitor discharge loop increases when the DC side fails, resulting in a decrease of the voltage across the current-limiting inductor, but the voltage of the current-limiting inductor at both ends of the fault line is always greater than 0.06 KV. The solution can reliably identify faults.

Table 2. Detection results of faults with various resistances.

| Fault types | Fault location | Fault resistance/Ω | $U_{Lm}$ | $U_{Ln}$ | $U_{Lp}$ | $U_{Ln}$ | $S$ | $S_b$ | Fault detection results |
|-------------|----------------|---------------------|---------|---------|---------|---------|-----|-----|-------------------------|
| Pole-to-ground | F1 | 0 | 4.154 | -0.219 | 4.146 | 0.241 | S=1 | 0 | Positive-pole fault |
| | | 1 | 4.053 | -0.179 | 4.086 | 0.114 | S=1 | 0 |
| | | 10 | 3.756 | -0.109 | 3.764 | 0.012 | S=1 | 0 |
| | | 20 | 3.566 | -0.002 | 3.558 | 0.023 | S=1 | 0 |
| Pole-to-ground | F2 | 0 | 0.027 | 4.294 | -0.057 | 5.865 | S=1 | 0 |
| | | 1 | 0.202 | 5.780 | -0.117 | 3.620 | S=1 | 0 |
| | | 10 | 0.135 | 4.984 | -0.177 | 3.579 | S=1 | 0 |
| | | 20 | 0.096 | 4.428 | -0.155 | 2.934 | S=1 | 0 |
| Pole-to-pole | F3 | 0 | 4.067 | -4.912 | 7.484 | 7.764 | S=1 | 0 |
| | | 1 | 4.652 | 4.701 | 7.759 | 7.516 | S=1 | 0 |
| | | 10 | 4.183 | 4.155 | 6.559 | 6.627 | S=1 | 0 |
| | | 20 | 3.591 | 3.572 | 5.836 | 5.821 | S=1 | 0 |
| DC Bus | F4 | 0 | -3.554 | -3.753 | 4.125 | -4.877 | 0 | S=1 |
| | | 1 | -3.572 | -3.430 | 4.034 | -4.910 | 0 | S=1 |
| | | 10 | -2.908 | -2.878 | 5.186 | -3.546 | 0 | S=1 |
| | | 20 | -2.495 | -2.442 | -2.814 | -2.849 | 0 | S=1 |

Table 3. Detection results of faults with various fault distances.

| Fault types | Fault location | Fault distance/km | $U_{Lm}$ | $U_{Ln}$ | $U_{Lp}$ | $U_{Ln}$ | $S$ | $S_b$ | Fault detection results |
|-------------|----------------|-------------------|---------|---------|---------|---------|-----|-----|-------------------------|
| Pole-to-ground | F1 | 0 | 4.507 | -0.201 | 2.304 | 0.035 | S=1 | 0 |
| | | 3 | 3.754 | -0.212 | 2.862 | 0.032 | S=1 | 0 |
| | | 6 | 3.424 | -0.158 | 3.419 | 0.061 | S=1 | 0 |
| | | 9 | 3.043 | -0.171 | 4.003 | 0.077 | S=1 | 0 |
| Pole-to-ground | F2 | 0 | 0.141 | 4.349 | -0.208 | 3.003 | S=1 | 0 |
| | | 2 | 0.035 | 4.003 | -0.314 | 3.222 | S=1 | 0 |
| | | 6 | 0.011 | 3.685 | -0.021 | 3.658 | S=1 | 0 |
| | | 8 | 0.011 | 2.957 | -0.149 | 4.469 | S=1 | 0 |
| Pole-to-pole | F3 | 0 | 6.153 | 6.117 | 3.702 | 3.624 | S=1 | 0 |
| | | 2 | 5.224 | 5.376 | 4.161 | 4.140 | S=1 | 0 |
| | | 4 | 4.700 | 4.894 | 6.066 | 6.482 | S=1 | 0 |
| | | 6 | 4.097 | 4.000 | 5.165 | 5.212 | S=1 | 0 |
| | | 8 | 3.748 | 3.813 | 6.166 | 6.622 | S=1 | 0 |

5.2.2. The effect of the fault distance on the protection scheme. The worst case of the fault resistance should be considered to prove that the protection scheme is not affected by the fault distance, that is,
the fault resistance to be set to 20Ω. It can be seen from Table 3 that with the increase of the fault distance, the DC line fault pole m-terminal current-limiting inductor voltage is gradually reduced, the n-terminal current-limiting inductor voltage gradually increases, and the current-limiting inductor voltage at both ends of the fault line is always greater than the protection threshold.

6. Conclusion
In this paper, according to the DC line current-limiting inductor voltage, a protection scheme suitable for multi-terminal flexible DC distribution network is proposed. The protection scheme has the following characteristics: 1) Protecting the full length of the line; 2) Identifying faults in the area and outside and DC bus faults; 3) Meeting the requirements of the DC distribution network for protection quick-moving within 3ms; 4) Having strong tolerance fault resistance capability.

Acknowledgments
This paper and its related research work are supported by Shanxi Province Science and Technology Major Project (No.20181102028).

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