A DC fault identification scheme for multi-terminal VSC-LVDC system based on voltage of current-limiting reactor

Panbao Wang1,4, Hongmei Sun1, Xin Hao1, Wei Su2, Dong Yuan3, Wei Wang1 and Dianguo Xu1

1 Harbin Institute of Technology, Harbin 150001, China;
2 Jiangsu Electric Power Company Research Institute, Nanjing 211103, China;
3 State Grid Jiangsu Electric Power Company, Nanjing 210024, China
4 Email: wangpanbao@hit.edu.cn

Abstract. The rapid and effective identification of DC faults is one of the key technologies for the development of multi-terminal DC (MTDC) system based on voltage source converter (VSC). The DC system fault current is characterized of high increasing speed and wide influence range. At present, the peak current and the rising speed of the fault current can be limited by current-limiting circuits, which are serially connected at both ends of the DC line. In this paper, the DC fault characteristics of a three-terminal DC system with DC line current-limiting reactors are analysed. On this basis, a fast identification method for DC faults in MTDC system according to the voltage across the line current-limiting reactor is proposed. The proposed scheme can quickly identify the fault location, the fault type and the fault pole. Finally, the effectiveness of the proposed fault detection scheme is verified by simulations. The simulation results show that the proposed method is still effective when the fault resistance and fault distance change, and is able to realize the rapid and accurate detection of DC faults.

1. Introduction
Voltage source converter (VSC) based low-voltage DC (LVDC) has fast and flexible active and reactive power control ability, which can improve the stability of the system and easily form a MTDC system [1-5]. With the rapid development of renewable energy power generations, VSC-based DC systems has been widely applied to renewable energy generations, multi-terminal DC transmission, sub-transmission and distribution systems, shipboard power supplies and other fields [6-11].

DC fault protection of VSC-based DC systems is one of the key technologies for its development. The main technical difficulties include the reliable identification and fast isolation of faulty lines [12-17]. In [18], handshaking method to identify the fault line is proposed. This method is simple and reliable, but the recognition speed is slow, and there is a short-time power failure phenomenon in the non-faulty part, which reduces the reliability of the power supply. The traveling wave protection and current differential protection for DC lines are proposed in [19] and [20]. Current differential protection needs to collect two-terminal electrical quantities, and there is a communication delay problem, while traveling wave protection lacks uniform and effective setting method, and backup protections are needed when traveling waves are too weak to trigger the protection devices. In [21], the module maximum of wavelet is proposed to detect and locate the DC faults. The method has the ability of anti-lightning protection. However, the second generation wavelet transform adopted in this scheme is complicated, and the description of the fault difference is not clear enough.
Based on the three-terminal VSC-LVDC system, detailed characteristics of the voltage across the line current-limiting reactor of the fault side after fault occurrence are analysed in this paper, and proposes a fast fault detection scheme. This scheme uses the single-terminal voltage amplitude across the line current-limiting reactor to identify the fault location, and to determine the fault type and fault pole by using the voltage amplitude difference between the positive-pole and negative-pole line current-limiting reactor. Finally, the feasibility of the scheme under different fault resistances and fault distances is verified by simulations.

2. Topology and fault characteristics analysis of a three-terminal VSC-LVDC system

The structure of a three-terminal VSC-LVDC system is shown in Figure 1. The system consists of converters, transformers, converter reactors, DC-side capacitors, DC transmission lines and line current-limiting reactors, where the converter adopts a two-level topology structure.

![Figure 1. Structure of a three-terminal VSC-LVDC system.](image)

Two typical DC faults in VSC-based DC system are pole-to-pole and pole-to-ground fault respectively. The pole-to-ground fault feature is related to the grounding mode of the DC system, and the typical grounding method is that the neutral point of the converter connects the earth. When the fault occurs, there will be a large fault current and transient voltage. The pole-to-pole fault is more harmful, and its fault characteristics are independent of the grounding mode.

![Figure 2. Equivalent circuit under fault condition: (a) pole-to-pole fault, (b) pole-to-ground fault.](image)

Taking the converter station 1 as an example for analysis, the equivalent circuit of the positive-to-ground fault and the pole-to-pole fault are shown in Figure 2 (a) and (b). Because the IGBT has a reliable self-protection function in the actual project, it can be turned off immediately after the DC fault occurs. Therefore, it is assumed in this paper that the converter station is immediately locked after the fault occurs. Meanwhile, due to the inertia of VSC-LVDC system and the special structure characteristic of DC side parallel capacitance, the DC line fault characteristics can be characterized by different stages [22]. The first stage of the both DC faults is the capacitor discharge stage. At this stage, the converter IGBT is turned off, the AC-side current does not increase, the DC-side capacitor voltage attenuates, and the DC current increases. In order to ensure the action of fast protection and tripping of DC circuit breaker before the zero-crossing time of DC capacitor voltage oscillation, it is necessary to identify the fault at this stage.
In Figure 2, $U_{dc1}$ is the DC-side voltage, $U_{Lc1p2}$ and $U_{Lc1n2}$ are the voltages of the positive-pole and negative-pole line current-limiting reactors respectively, $i_{pp1}$ is the line current when the pole-to-pole short-circuit fault occurs and $i_{pg1}$ is the line current when the pole-to-ground fault occurs. $L_{c1p2}$ and $L_{c1n2}$ are positive-pole and negative-pole line current-limiting reactor respectively, and their inductance values are the same. $R_f$ is the fault resistance, $R_{d1}$ and $L_{d1}$ are the π-model equivalent resistance and inductance of the positive and negative line from the VSC to the fault point. Considering that the DC-side capacitance $C$ is much larger than the parallel capacitance of the π-model equivalent circuit, the influence of the equivalent capacitance of the DC line is ignored.

According to Figure 2(a), the fault characteristics of the capacitor discharge stage after the occurrence of the pole-to-pole short-circuit fault are analysed by ignoring the coupling effect of the non-fault-side current. At this stage, the DC-side capacitor, the current-limiting reactor and the line equivalent reactance constitute the RLC circuit, and the following equations can be derived by using KVL:

\[ L_1 \frac{di_{pp1}}{dt} + R_i i_{pp1} - U_{dc1} = 0 \]  
\[ i_{pp1} = -C_1 \frac{dU_{dc1}}{dt} \]  

When $R_i < 2\sqrt{L_1 / C_1}$, the solution of the (1) will result in an underdamped response:

\[ i_{pp1}(t) = M_1 e^{-\delta_1 t} \sin(w_1 t + \alpha_1) \]  
\[ U_{Lc1}(t) = -\frac{L_{c1}}{2} M_1 w_0 e^{-\delta_1 t} \sin(w_1 t + \alpha_1 - \beta_1) \]  

where

\[ \delta_1 = \frac{R_i}{2L_1}, \quad L_1 = L_{c1} + L_{d1}, \quad R_i = R_{d1} + R_f \]  
\[ w_1^2 = \frac{1}{L_1 C_1} - \delta_1^2, \quad w_0^2 = w_1^2 + \delta_1^2 = \frac{1}{L_1 C_1}, \quad \alpha_1 = \arctan \frac{A_1}{B_1}, \quad \beta_1 = \arctan \frac{w_1}{\delta_1}. \]  

The amplitude of voltage across the line current-limiting reactor at the fault time can be obtained from (4):

\[ U_{Lc1}(t_0) = \frac{1}{2} \times \frac{L_{c1}}{L_1} \times (U_{01} - R_i I_{01}) \]  

When $R_i > 2\sqrt{L_1 / C_1}$, the solution of the (2) result in an overdamped response:

\[ i_{pp1}(t) = m_1 e^{\lambda_1 t} + m_2 e^{\lambda_2 t} \]  
\[ U_{Lc1}(t) = \frac{L_{c1}}{2} (m_1 e^{\lambda_1 t} + m_2 e^{\lambda_2 t}) \]  

where

\[ \lambda_{1,2} = -\delta_1 \pm \sqrt{\delta_1^2 - w_0^2}, \quad m_1 = \frac{1}{\lambda_1 - \lambda_2} \left( \frac{U_{01} - R_i I_{01}}{L_1} - \lambda_2 I_{01} \right), \quad m_2 = I_{01} - m_1. \]  

The amplitude of voltage across the line current-limiting reactor at $t_0$ can be obtained by (7):

\[ U_{Lc1}(t_0) = \frac{1}{2} \times \frac{L_{c1}}{L_1} \times (U_{01} - R_i I_{01}) \]  

It can be seen from (5) and (8) that for the underdamped response in the case of $R_i < 2\sqrt{L_1 / C_1}$ and the overdamped response in the case of $R_i > 2\sqrt{L_1 / C_1}$, the voltage across the line current-limiting reactor at the fault time are the same.
According to Figure 2(b), the fault characteristics of the capacitor discharge stage after the occurrence of the positive-to-ground fault are analysed by ignoring the coupling effect of the non-fault-side current. At this stage, the DC-side capacitor, the current-limiting reactor and the line equivalent reactance constitute the RLC circuit, and the following equations can be derived by using KVL:

\[ \frac{di_{pg1}}{dt} + R_{pg1}i_{pg1} - U_{dc1} = 0 \]  
(9)

\[ i_{pg1} = -C_{1} \frac{dU_{dc1}}{dt} \]  
(10)

It can be found that when the fault resistance of pole-to-ground fault is twice of pole-to-pole short-circuit fault, the current of positive line and the voltage across line current-limiting reactor of positive line under positive-to-pole fault are the same as those under pole-to-pole short-circuit fault. However, compared with the pole-to-ground fault, the positive and negative poles are affected equally in the case of pole-to-pole fault, so the range of influence is wider and the damage to the system.

To verify the above analysis, the three-terminal VSC-LVDC system shown in Figure 1 is tested in different fault conditions. Figure 3(a) and (b) show the voltage across the line current-limiting reactor of each positive line when the pole-to-pole short-circuit fault and positive-to-ground fault happens at 10 km away from VSC1, the fault time \( t = 0.5 \) s and the fault resistance is 20 \( \Omega \) and 40 \( \Omega \), respectively. In practical engineering, the pole-to-pole short-circuit fault resistance is very small, and pole-to-pole high-impedance ground fault will have a large fault resistance [23].

![Figure 3. Simulation results of voltage across the line current-limiting reactor positive-line during DC faults: (a) pole-to-pole fault (20 \( \Omega \)), (b) positive-to-ground fault (40 \( \Omega \)).](image)

It can be seen that when a DC fault occurs, the voltage amplitude across the line current-limiting reactor of the fault side will be greatly changed, and the voltage amplitude across the line current-limiting reactor of the fault side and the non-fault side is clearly distinguished. Therefore, the voltage amplitude across the line current-limiting reactor is selected as the criterion of DC fault detection.

### 3. Fault Detection Criterion and related setting

#### 3.1. Fault trigger criterion

According to the above analysis, the DC fault can be detected by detecting whether the voltage across the current-limiting reactor exceeds the threshold. The fault triggering criterion is shown as follows:

\[ |U_{Lc/p2(i)}| > U_{TH(i)\text{set}} \quad \text{or} \quad |U_{Lc/n2(i)}| > U_{TH(i)\text{set}} \]  
(11)

where \( U_{Lc/p2} \) and \( U_{Lc/n2} \) are the positive-pole and negative-pole line current-limiting reactor voltages respectively. \( i \) represents the converter station \( i \) side, and its value ranges is \( 1 \leq i \leq 3 \). \( U_{TH(i)\text{set}} \) is the action threshold value for the DC fault identification. If the criterion (11) is satisfied, then it can be determined that the system has a DC fault.

#### 3.2. Fault side criterion

It can be seen from Figure 3 that When a DC fault occurs in the system, since the impedance of the capacitor discharge loop on the non-fault side is larger than that on the fault side, the voltage across
the non-fault-side line current-limiting reactor is much smaller than that of the fault-side. The fault side identification criterion can be expressed as:

\[
\frac{U_{Lcip}}{2} > U_{TH2(set)} \quad \text{or} \quad \frac{U_{Lcin}}{2} > U_{TH2(set)}
\]  

\(U_{TH2(set)}\) is the action threshold value for the fault side identification. If the criterion (12) is satisfied, then it can be determined that the DC fault occurred on the DC side of converter station \(i\).

3.3. Fault type criterion

From the analysis of the second section, it can be seen that the voltage amplitude across the line current-limiting reactor at the fault side is almost the same after the pole-to-ground fault and pole-to-pole short-circuit fault occur, so the fault types cannot be distinguished only by using the voltage amplitude across the line current-limiting reactor at the fault side. Compared with the pole-to-pole short-circuit fault, the voltage across the line current-limiting reactor of fault pole is much larger than that of non-fault pole for a pole-to-ground fault. Therefore, the difference of voltage amplitude across the line current-limiting reactor of positive-pole and negative-pole can be used to judge the fault type. The fault type identification criterion can be expressed as:

\[
\begin{align*}
\frac{U_{Lcip}}{2} - \frac{U_{Lcin}}{2} > U_{TH3(set)}, & \quad \text{pole-to-ground fault} \\
\frac{U_{Lcip}}{2} - \frac{U_{Lcin}}{2} < -U_{TH3(set)}, & \quad \text{pole-to-pole fault}
\end{align*}
\]  

\(U_{TH3(set)}\) is the action threshold value for the fault type identification. If the first condition of criterion (13) is satisfied, the fault is a pole-to-ground fault, otherwise the fault is a pole-to-pole fault.

3.4. Fault pole criterion

After the fault type identification is completed, if the fault is determined as a pole-to-ground fault, further identification of the fault pole is needed. From the above analysis, it is found that the voltage amplitude across the line current-limiting reactor of the fault pole is much larger than that of the non-fault pole when the pole-to-ground fault occurs. The fault pole identification criterion is:

\[
\begin{align*}
\frac{U_{Lcip}}{2} - \frac{U_{Lcin}}{2} > U_{TH4(set)}, & \quad \text{positive-to-ground fault} \\
\frac{U_{Lcip}}{2} - \frac{U_{Lcin}}{2} < -U_{TH4(set)}, & \quad \text{negative-to-ground fault}
\end{align*}
\]  

\(U_{TH4(set)}\) is the action threshold value for the identification of the fault pole. If the difference of voltage amplitude across the line current-limiting reactor between the positive-pole and negative-pole of fault side is greater than \(U_{TH4(set)}\), it is determined to be a positive-to-ground fault. If the difference is less than the opposite of the \(U_{TH4(set)}\), it is determined to be a negative-to-ground fault.

3.5. Setting of fault detection threshold

3.5.1. Setting of fault trigger threshold \(U_{TH1(set)}\) When the system is operating normally, the voltage amplitude across the line current-limiting reactor should be 0 under ideal conditions. Actually, by considering the influence of noise and harmonic interference, the fault triggering threshold value should be a value greater than zero.

When the fault occurs at the public point of the three-terminal, the distance from the fault location to the three converter stations is the same, the impedance of the capacitor discharge loop is large, and the three-terminal are least affected by the fault. Therefore, when the DC fault occurs at this position, the minimum value of the voltage amplitude across the line current-limiting reactor of three-terminal is used as a reference to set the fault trigger threshold value \(U_{TH1(set)}\). Additionally, it can be found from (8) that the voltage across the line current-limiting reactor at the fault time is affected by the fault resistance, so the fault resistor should be taken into account when selecting \(U_{TH1(set)}\). The fault resistance will not be very large when the pole-to-pole short-circuit fault occurs, but fault resistance may be very large for a pole-to-ground fault. Therefore, the fault resistance is set to 1 Ω when the
pole-to-pole short-circuit fault occurs at the common point of the three-terminal and 100 Ω for pole-to-ground fault. In summary, the threshold $U_{TH1(set)}$ of fault trigger action is adjusted as follows:

$$U_{TH1(set)} = K_{rel1} \min_{t \in [2]} \left| U_{Leip/2} \right|_{(\text{fault moment})} \left| U_{Lein/2} \right|_{(\text{fault moment})}$$

(15)

where $K_{rel1}$ is the setting coefficient of fault trigger. In order to ensure the accuracy and speed of fault detection, $K_{rel1}$ takes a value of 0.6.

### 3.5.2. Setting of fault side identification threshold $U_{TH2(set)}$

In order to ensure effective identification of fault side, the selection of $U_{TH2(set)}$ should make this threshold value smaller than the voltage amplitude across the line current-limiting reactor of fault side, which is the maximum voltage amplitude across the current-limiting reactors of any line. Meanwhile, this threshold should be larger than the voltage amplitude across the line current-limiting reactor of non-fault side lines.

Similarly, the $U_{TH2(set)}$ is set based on the voltage amplitude across the line current-limiting reactor obtained under the DC fault of the three-terminal common intersection set in 3.5.1:

$$U_{TH2(set)} = K_{rel2} \min_{t \in [2]} \left| U_{Leip/2} \right|_{(\text{fault moment})} \left| U_{Lein/2} \right|_{(\text{fault moment})}$$

(16)

where $U_{Leq} = \max_{t \in [2]} \left| U_{Leip/2} \right|_{(\text{fault moment})} \left| U_{Lein/2} \right|_{(\text{fault moment)}}$, $K_{rel2}$ is the setting coefficient of fault side identification. In order to ensure the rapid and accurate identification of the fault side, $K_{rel2}$ takes a value of 1.

### 3.5.3. Setting of fault type identification threshold $U_{TH3(set)}$

Theoretically, the voltage amplitude difference between the line current-limiting reactor of positive-pole and negative-pole is 0 for pole-to-pole short-circuit fault. However, by considering that there will be noise and harmonic existing in the practical schemes, the amplitude difference is not strictly 0. In the case of a pole-to-ground high-impedance ground fault with a fault resistance of 100 Ω occurs at the three-terminal common point, the minimum value of the voltage amplitude across the line current-limiting reactor of three-terminal is used as a reference value, and the fault type identification threshold $U_{TH3(set)}$ can be expressed as:

$$U_{TH3(set)} = K_{rel3} \min_{t \in [2]} \left| U_{Leip/2} \right|_{(\text{fault moment})} \left| U_{Lein/2} \right|_{(\text{fault moment})}$$

(17)

where $K_{rel3}$ is the setting coefficient of fault type identification. In order to ensure the rapid and accurate identification of the fault type, $K_{rel3}$ takes a value of 0.6. After the fault type is effectively identified, if it is identified as a pole-to-ground fault, it is necessary to further judge the polarity of the fault line.

### 3.5.4. Setting of fault pole identification threshold $U_{TH4(set)}$

Similarly, the fault pole identification threshold $U_{TH4(set)}$ can be set based on the minimum voltage amplitude across the line current-limiting reactor which is obtained from the DC fault of the three-terminal common point described in 3.5.3:

$$U_{TH4(set)} = K_{rel4} \min_{t \in [2]} \left| U_{Leip/2} \right|_{(\text{fault moment})} \left| U_{Lein/2} \right|_{(\text{fault moment})}$$

(18)

where $K_{rel4}$ is the setting coefficient of fault pole identification. In order to ensure the rapid and accurate identification of the fault pole, $K_{rel4}$ takes a value of 0.8.

### 4. Simulation results

In order to validate the DC fault identification scheme in the three-terminal VSC-LVDC system, a simulation model is implemented in MATLAB/Simulink. At the VSC1 side, constant DC voltage control is adopted, and constant active power control is implemented at the VSC2 and VSC3 side. The specific simulation parameters are shown in Table 1.

#### 4.1. Feasibility verification of the proposed scheme

Figure 4(a) shows the voltage waveforms across the line current-limiting reactor of the three-terminal when the pole-to-pole short-circuit fault happens at 20 km away from VSC1, the fault resistance is 0...
Ω and the fault time \( t=0.5 \) s. Figure 4(b) and (c) show the voltage waveforms across the line current-limiting reactor of the three-terminal when the positive-to-ground fault happens at 20 km away from VSC 1, and the fault time \( t = 0.5 \) s, the fault resistance is 0 Ω and 20 Ω respectively.

![Figure 4](image)

**Figure 4.** Simulation results of voltage waveforms across the line current-limiting reactor of VSC 1 during DC faults: (a) pole-to-pole fault (0 Ω), (b) positive-to-ground fault (0 Ω), (c) positive-to-ground fault (20 Ω).

| Parameter                  | Nominal Value |
|-----------------------------|---------------|
| DC-link voltage \( U_{dc} \) | 10 KV         |
| DC-link capacitance         | 1000 μF       |
| DC line resistance          | 0.006 Ω/km   |
| DC line inductance          | 0.795 mH/km  |
| DC line length              | 100 km        |
| Power rating of station 1   | 43 MW         |
| Power rating of station 2   | 45 MW         |
| Power rating of station 3   | 38 MW         |

Table 1. Simulation parameters.

It can be seen that after occurring the pole-to-pole short-circuit fault and the pole-to-ground fault, the voltage across the DC-line current-limiting reactor of the fault-side is greater than the fault trigger threshold of 135.072 V, which enable the scheme quickly identifies the fault. Then, comparing the voltage amplitude across the line current-limiting reactor of fault-side with the fault side identification threshold of 225.122 V, it can be identified that the fault occurs on the side of VSC 1. Then, for the pole-to-pole short-circuit fault, the difference between the voltage amplitudes across the line current-limiting reactors of positive and negative line of the fault-side are calculated to be 0, which is lower than the fault type identification threshold of 136.240 V, therefore it can be determined that the pole-to-pole short-circuit fault occurs on the line of VSC 1 side.

The pole-to-pole short-circuit fault and positive-to-ground fault occurring at VSC 1 with different fault resistances are investigated in this section. The positive-to-ground fault resistance is set from 0 Ω to 100 Ω, meanwhile, fault distance is 10 km and the fault time \( t=0.5 \) s. Figure 5 shows the corresponding simulation results of voltage variations across the line current-limiting reactor at the fault side.

![Figure 5](image)

**Figure 5.** Simulation results with different fault resistances: (a) fault trigger and fault side identification of pole-to-pole fault, (b) identification of fault type and fault pole, (c) fault trigger and fault side identification of positive-to-ground fault, (d) identification of fault type and fault pole.

It can be seen that with the increase of the fault resistance, the impedance of the DC side capacitor discharge loop of the converter station increases, and the voltage across the line current-limiting...
reactor decreases, but the voltage across the line current-limiting reactor is always greater than the fault trigger threshold of 135.072 V, therefore the fault detection and fault side identification are effective. It can be seen from Figure 5 (c) that as the fault resistance increases, the difference between the voltage amplitudes across the current-limiting reactors of the fault side decreases under the pole-to-ground fault, however the fault type and fault pole identification method are still valid.

4.2. Influence of fault distance
The pole-to-pole short-circuit fault and the positive-to-ground fault occurring at converter station 1 with different fault distances are investigated from 0 to 80 km. In this simulation scenario, the fault resistance is 0 Ω and the fault time $t=0.5$ s. Figure 6 shows the results of voltage variations across the line current-limiting reactor at the fault side.

![Figure 6](image)

**Figure 6.** Simulation results with different fault distances: (a) fault trigger and fault side identification of pole-to-pole fault, (b) identification of fault type and fault pole, (c) fault trigger and fault side identification of positive-to-ground fault, (d) identification of fault type and fault pole.

It can be seen that with increasing of the fault distance, the impedance of the DC side capacitor discharge loop increases, and the voltage amplitude across the line current-limiting reactor decreases. However, even if the fault occurs at the common point of the three-terminal and the fault resistance is large, the fault triggering criterion, the fault side identification criterion, the fault type identification criterion and the fault pole identification criterion are still valid.

5. Conclusions
For the three-terminal VSC-LVDC system with line current-limiting reactor, a fault detection scheme based on the voltage across the line current-limiting reactor is proposed in this paper. Based on the simulation in MATLAB, it is verified that the proposed scheme is able to detect the DC faults, as well as identify the fault side, fault type and fault pole quickly and accurately. This scheme can realize the identification of DC fault of the whole line, and the fault detection is based on the locally measured system variables, which does not need communication, effectively reduces the time delay, can identify DC line fault quickly and accurately in 2ms, and has good rapidity. Moreover, when the fault resistance and fault distance changes, the proposed DC fault identification scheme can still maintain a high accuracy and stable performance, but the selection of threshold in this method still needs to be adjusted by simulation results.

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