DC Fault Challenge in Multi-Terminal VSC-HVDC System

- VSC typically cannot block DC fault current
- High fault current rising rate
- No zero-crossing point of DC current
- Small power device overcurrent margin
- Small DC voltage range for system continuous operation

Hybrid DC Circuit Breaker

- Low operation loss
- Fast opening time (~2ms)

Proposed DC Fault Protection Strategy

1. Two-step DC fault detection method in circuit breaker
   - Primary detection: Travelling wave based method
     - If $V_L > dV_{TH}$: Trip
     - Else: Stand by
   - Secondary detection: Current differential method
     - If $I_{diff} > dI_{TH}$: Trip
     - If $I_{diff} < dI_{TH}$: Block for dt time; Stand by

2. Converter temporary blocking criteria in each station
   - Pole to pole fault
     - Overcurrent: $I_{dc} > 2.0$ p.u. OR DC overvoltage: $V_{dc} > 1.5$ p.u.
   - Pole to ground fault
     - Overcurrent: $I_{dc} > 1.5$ p.u. AND DC undervoltage: $V_{dc} < 0.8$ p.u.

3. Converter recovery strategy after temporary blocked
   - Converter is de-blocked when DC voltage is within a safe range ([0.8 p.u., 1.2 p.u.]) for certain time (e.g. 50 ms)
   - Voltage margin control is used to avoid large DC voltage overshoot during the recovery process

Protection Methods in Literature

<table>
<thead>
<tr>
<th>Protection Method</th>
<th>Fault Clear Time (ms)</th>
<th>Recovery Time (ms)</th>
<th>DC System Shutdown</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. AC Circuit Breaker + High-Speed DC</td>
<td>~200 ms</td>
<td>~150 ms</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Mechanical Switch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Mechanical DC Circuit Breaker</td>
<td>~28 ms</td>
<td>—</td>
<td>Yes</td>
<td>Yes (Limited current)</td>
</tr>
<tr>
<td>(Passive-Resonance type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Mechanical DC Circuit Breaker</td>
<td>~14 ms</td>
<td>—</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(Active-Resonance type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Solid State DC Circuit Breaker</td>
<td>~4 ms</td>
<td>—</td>
<td>—</td>
<td>No</td>
</tr>
<tr>
<td>5. Hybrid DC Circuit Breaker</td>
<td>~9 ms</td>
<td>~150 ms</td>
<td>—</td>
<td>Near Future</td>
</tr>
<tr>
<td>6. Fault Tolerant Converter + High-Speed DC Mechanical Switch</td>
<td>~150 ms</td>
<td>~100 ms</td>
<td>Yes</td>
<td>Near Future</td>
</tr>
</tbody>
</table>

Test Results

- Different fault types (pole to pole, pole to ground)
- Different fault locations
- Different fault impedances
- Different circuit breaker delay times

DC Fault Protection of Multi-Terminal VSC-HVDC System with Hybrid DC Circuit Breaker