Fast Fault Detection and Current Limiting Strategy of HVDC Circuit Breaker

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Abstract. HVDC transmission has become the most valuable engineering technology because of its own advantages. But the rapid detection and isolation of DC side faults has been one of the major technical matters in the development of DC grids. High-voltage DC circuit breaker is an important equipment to solve this problem, and becomes the current research hotspot. According to the process of HVDC breaker, this paper analyzes the fault detection and current limiting control of HVDC breakers, and proposes a fault detection method based on ROCOV (Rate Of Change Of Voltage) and a current limiting strategy of operation of arresters by sequence. It can reduce the operation time of the circuit breaker and the peak value of the fault current. Finally, simulation analysis is performed on the PSCAD/EMTDC to verify the correctness of the method.

1. Introduction

The uneven distribution of resources in China determines the demand for large-capacity long-distance power transmission in the future. Due to the power loss of the HVDC transmission line is relatively small and it does not have transmission limit, HVDC has become a hot topic in the current research. DC circuit breaker is the key equipment in HVDC transmission project [1, 2]. Using DC circuit breakers to isolate fault points can make it unnecessary for the DC grid to block all converter stations when a line fails and does not affect the normal operation of other lines, which has good economics. [3, 4] The new type of hybrid DC circuit breaker combines the characteristics of small on-state losses of mechanical DC breakers and fast switching of solid-state DC breakers, which has great research value [5]. The conventional DC circuit breaker fault detection protection principle mostly depends on the communication between the stations. The communication delay causes a long total time of the operation process, which will limit the long-distance transmission of the flexible power grid [6]. The
fault current of the HVDC transmission increases so rapidly that the hazard is great. This requires the time for circuit breaker operation and the magnitude of the fault current are as small as possible. Therefore, according to the characteristics of DC line faults, this paper proposes new protection strategies for the fast fault detection and current limiting control of DC circuit breakers. The cooperation between them can greatly improve the reliability of the system.

2. Fast Circuit Breaker Detection of DC Circuit Breakers

The fast fault detection method proposed in this paper is based on the change of ROCOV to determine whether the line is faulty. Figure 1 is a simple topology of a two-terminal flexible DC transmission system with a transmission line length of 200 km. The DC circuit breaker is installed at the exit of each line, and the line voltage is measured in real time to calculate the ROCOV value.

![Figure 1. Typical two-terminal flexible DC transmission system](image1)

Figure 2 shows the change of line voltage detected by the circuit breaker when the fault location was at a different distance from the circuit breaker at one end in figure 1. The fault occurred when $t=2.5s$. It can be seen that the line voltage suddenly changes [7] in a very short time after a fault occurred. Even if the fault occurred at the point farthest from the point where the circuit breaker is measured, the voltage waveform is steep enough to be detected by setting an appropriate operation threshold.

![Figure 2. Change in line voltage detected by circuit breakers at different fault points](image2)

According to the characteristics of DC faults, the line voltage will suddenly change at the moment of failure, at this time the absolute value of the voltage change rate will become very large; while the line voltage without faulty is relatively stable, the voltage change rate is small. Therefore, the criteria for fault detection can be found as follows:
In the formula (1), $V_L$ is the voltage of the detection circuit, \( \Delta \) is a differential operator, refers to $\frac{d}{dt}$, and the same as below. \( |\Delta V_{L_{\text{set}}}| \) is the ROCOV threshold of the preset protection start. The threshold can be selected by setting the ROCOV value measured when the fault location is at the most distant point from the circuit breaker. The formula is:

$$|\Delta V_{L_{\text{set}}}| = K_L |\Delta V_{L_{\text{min}}}|$$

In the formula (2), $V_L$ is the voltage of the measured line to ground, and $K_L$ can be selected from 0.8 to 0.9 according to the actual engineering requirements. \( |\Delta V_{L_{\text{min}}}| \) represents the ROCOV value measured by the circuit breaker at the line farthest from the fault location.

This method is easy to implement and has high reliability. Because the fault detection of this method is local, it reduces the communication delay of about 1ms compared with the conventional traveling wave protection and differential protection \[8, 9\], so it improves the fault detection speed.

3. DC circuit breaker current limiting control

Figure 3 is a schematic diagram of a typical hybrid DC circuit breaker.

There are dozens or even hundreds of sub-modules in the auxiliary branch of an actual project. To simplify the analysis, four sub-modules of parallel arresters are used as an example. In normal operation, the main branch mechanical switch $S$ is closed, the IGBT switch $Tm$ is closed, and T1-T4 is in ON state. After a line fault occurs, the action of the DC circuit breaker can be divided into three steps:

1. The system sends an open signal to the circuit breaker, then the main branch IGBT switch $Tm$ is in OFF state, and the fault current is transferred from the main branch to the auxiliary branch;
2. When the current of the main branch drops to zero, the mechanical switch $S$ opens;
3. When the mechanical switch $S$ reaches the withstand voltage level, turn off T1-T4, the arrester operates and the energy has been absorbed, finally the fault current gradually becomes zero.

The method can realize the arc-free breaking of the mechanical switch and reduce the impact of the fault current on the device. After the DC side short-circuit fault occurs, the magnitude of the fault current is shown in formula (3):

$$i_{dc} = I_{dcN} + \frac{1}{L_{dc}} \int V_{dc} dt$$
Where $I_{dcN}$ is the current when the DC system is in normal operation; $L_{dc}$ is the system inductance, and $V_{dc}$ is the DC system equivalent voltage.

From equation (3) it can be seen that there are three ways to reduce the fault current. First one, the value of $L_{dc}$ can be increased, but increasing the system inductance will destabilize the system's small signal and reduce the sensitivity of the short-circuit current to the reactance. This method should not be used in actual projects [10]. Secondly, reduce the time from failure occurrence to failure removal, which can be represented by $\Delta t$. If it is possible to achieve fast fault detection of a DC circuit breaker, the total time for the circuit breaker to handle the fault can be reduced, so as to the fault current. The third method is to reduce the equivalent voltage of the DC system at the time of fault. The conventional method of breaking is to reduce the DC system equivalent voltage by turning off the IGBT and switching the arrester to the system to produce counter electromotive force. The formula for the fault current after the arrester is put into use is as follows:

$$i_{dc} = I_{dcN} + \frac{1}{L_{dc}} \int [V_{dc} - n(t)V_{var}] dt$$

(4)

Where $n(t)$ is the number of IGBT valves that are in off, and the value is an integer between 0 and 4. $V_{var}$ is the back-EMF value formed by a group of arrester inputs. This value is approximately constant during the breaking process.

From the step 3 of the DC circuit breaker operation process, it can be seen that all the arrester groups operate at the same time according to whether the mechanical switch $S$ reaches a withstand voltage level. To the several arresters connected with the IGBT submodules in parallel, the surge arrester can be operated by sequence based on the withstand voltage level of the mechanical switch. When the mechanical switch is fully disconnected and reaches the withstand voltage level, all surge arresters will be put into operation. [11] Assuming that the time from the occurrence of the fault to the time when the four groups of surge arresters are put into use is $T_1$, and the DC system equivalent voltage is considered constant during this time, the magnitude of fault current before all surge arresters put into operation can be obtained from equation (3):

$$I_1 = I_{dcN} + \frac{V_{dc}}{L_{dc}} T_1$$

(5)

If the method of rapid detection of faults mentioned in the second part is applied, the peak value of the fault current is:

$$I_1' = I_{dcN} + \frac{V_{dc}}{L_{dc}} (T_1 - \Delta t)$$

(6)

Where $\Delta t$ is the time at which the conventional DC circuit breaker fault detects the communication delay. If the operation of arresters by sequence before the mechanical switch reaches the full withstand voltage level, equation (7) can be obtained:

$$I_1' = I_{dcN} + \frac{V_{dc}}{L_{dc}} T_1 - \frac{V_{var}}{L_{dc}} (\Delta t_1 + 2\Delta t_2 + 3\Delta t_3)$$

(7)

Among them, $\Delta t_1$, $\Delta t_2$, and $\Delta t_3$ are the time for switching one, two, and three surge arresters, respectively. It can be seen that the peak value of the fault current will be greatly reduced before the four surge arresters are fully in use.
4. Analysis and simulation

Combined with the analysis of the second and third parts, the total formula for the peak value of the fault current can be obtained as

\[ I_2 = I_{dcN} + \frac{V_{dc}}{L_{dc}}(T_1 - \Delta t) - \frac{V_{var}}{L_{dc}}(\Delta t_1 + 2\Delta t_2 + 3\Delta t_3) \]  

Equation (8) shows that the current limiting effect is significantly improved compared to equation (5):

\[ I_2 - I_1 = \frac{V_{dc}}{L_{dc}} \Delta t + \frac{V_{var}}{L_{dc}}(\Delta t_1 + 2\Delta t_2 + 3\Delta t_3) \]  

The first item on the right side of the equation (9) is the fault current component reduced by the fast fault detection; the second item is the fault current component reduced by the strategy of operation of arresters by sequence.

For the simulation of the operation process of the circuit breaker in PSCAD/EMTDC based on the above theory, some parameters of the simulation are as Table 1.

The time when the fault occurred is set at \( t=0.5s \). \( |\Delta V_{set}| \) obtained from equation (2) is 3500 kV/ms. The current-limiting result under various methods is shown in Figure 4.

**Table 1. System Parameters in PSCAD/EMTDC**

| Parameters                  | Value     |
|-----------------------------|-----------|
| DC voltage \( ±160kV \)    |           |
| Equivalent inductance \( 40\text{mH} \) |           |
| Equivalent load \( 100\Omega \) |           |
| On resistance of IGBT \( T_\text{m} \) \( 0.01\Omega \) |           |
| On resistance of IGBT \( T_1\text{-}T4 \) \( 0.3\Omega \) |           |
| Reference value for current control \( 2kA \) |           |

**Figure 4.** Comparison of the fault currents of the three current limiting methods

In Figure 4, \( I_1 \), \( I'_1 \), and \( I_2 \) represent the current limiting methods of equations (5), (6), and (8) respectively. It can be seen that \( I_2 \) further enhances the ability of current limiting on the basis of \( I'_1 \), and the limiting effects of the three methods are shown in Table 2.
| Table 2. Comparison of the Effects of Three Current Limiting Methods |
|---------------------------------------------------------------|
|                  | Operate time/s | Peak current/kA |
| Conventional current limiting methods | 0.5039        | 15.94          |
| Fast fault detection of current limiting methods              | 0.5030        | 12.82          |
| Operation of arresters by sequence + fast fault detection of current limiting methods | 0.5012        | 5.05           |

5. Conclusion
This paper presents a new type of DC circuit breaker current limiting control strategy by analyzing the operation of DC circuit breakers. Through the theory and simulation verification, the following conclusions are obtained:

1) The method of determining the occurrence of a fault based on the detection ROCOV of line reduces the communication delay time compared to the conventional protection strategy and has speed and reliability.

2) The current-limiting method of operation of arresters by sequence in hybrid circuit breaker can effectively reduce the peak value of the fault current, thereby reducing the damage to the equipment by inrush current.

3) The hybrid circuit breaker based on the ROCOV method to determine the fault occurrence and operation of arresters by sequence to limit the fault current can effectively use the advantages of both and reduce the operating time and peak fault current, which has highly research value.

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