Longitudinal Protection Scheme of HVDC Line Based On the Characteristics of Branch Current

Zhiming Xu*, Jun Liu, Tianyu Bai, Wenqiao Tang
School of Electrical Engineering, Shanghai DianJi University, Shanghai, China

*Corresponding author e-mail: 397216389@qq.com

Abstract. For the traditional high-voltage direct current (HVDC) lines with poor protection rapidity and low resistance to high resistance, this paper puts forward a kind of based on HVDC line reactance flat wave branch current changes of the longitudinal protection scheme. This scheme takes advantage of the fact that the specific harmonic component of the flat-wave reactance branch current is short-circuited by the equivalent dc filter bank when it is internal fault. The characteristics of no such harmonic component flow on the branch can be used as the basis to identify internal fault and external fault. In other words, when it is internal fault, the component of the flat-wave reactance branch is close to 0; The component of the flat wave reactance branch is much larger than 0 when it is external fault. Simulation results show that HVDC longitudinal protection scheme based on branch current characteristics can quickly and accurately identify fault types in various situations and has a strong ability to withstand transition resistance.

1. Introduction
Due to the severe natural environment and long transmission span of HVDC transmission line, the probability of fault is high. Studies have shown that line faults of dc transmission system account for more than 50% of the total number of faults, and the action accuracy of line protection is only 50% [1]. As a backup protection, longitudinal protection can effectively identify high-resistance faults and protect the full length of the transmission line [2]. However, considering the influence of fault distribution capacitance outside the zone, the delay even reaches the second level [3]. It is difficult to guarantee the quickness of relay protection.

Literature [4] proposed a method to construct voltage and current abrupt change phase angle difference based on S transformation, which combined with the principle of wavelet transform. But its too complex calculation, causes its actual project value to be not big. Literature [5] use the integral ratio of the inverse wave amplitude to identify faults inside and outside the zone, which improves the speed of backup protection. However, due to the attenuation characteristics of the reverse traveling wave, if the transmission span is too long, it is difficult to ensure that the protection range can cover the whole line. Literature [6] proposes a method to judge faults in and out of the dc line area with the impedance frequency characteristics of the dc filter in mind, although the method can quickly identify fault areas. But it is still difficult to extract the characteristic quantity.

Therefore, it is necessary to further study the longitudinal protection of HVDC lines. In this paper, a scheme is proposed to identify the fault location according to the current of the flat-wave reactance
branch in the rectifying side of HVDC line or the flat-wave reactance branch in the inverting side of HVDC line. This method makes use of the difference of shunt between HVDC line and flat wave reactance branch due to the difference of fault additional network. It can realize fast and accurate fault location judgment, and has lower communication requirements and shorter data window requirements.

2. HVDC system

2.1. Composition of bipolar HVDC system
As shown in figure 1, the system is mainly composed of rectifier station, inverter station and dc transmission line.

![Bipolar HVDC system](image)

Figure 1. Bipolar HVDC system

The M and N points in the figure are respectively the voltage and current detection points of the rectifying side and the inverting side of the dc transmission line. Is a flat-wave reactor, dc filters are installed on both sides of the dc line.

2.2. Analysis of dc filtering link
Flat-wave reactor and dc filter constitute the dc filter link. Currently, three-tuned or single-tuned dc filters are widely used in HVDC projects in China [7]. In actual dc engineering, the harmonic frequency of dc filter is more than one. Different dc filtering links have different impedance characteristic curves, all for filtering 12 and its multiples of harmonics [8].

According to literature [9], taking the filter 12/24/36 as an example of an engineering example, it is known that the impedance characteristics of the dc filter link are universal. When the frequency is 600/1200 and 1800, the impedance of the dc filter link is small, especially when the frequency is 600, the impedance amplitude of the dc filter \( Z_{1b} \) tends to 0, far less than that of other frequencies.

3. Analysis of internal fault and external fault on HVDC

3.1. Internal fault
Assuming the internal fault in the HVDC line occurs, the additional fault in the HVDC line as shown in figure 2 is obtained according to the superposition principle.

![Fault component network for internal fault](image)

Figure 2. Fault component network for internal fault
It can be seen from figure 2 that, when it is internal fault, the current of the rectifying side $I_r$ and the inverting side of the flat-wave reactance branch $I_i$ can be obtained from the shunt relationship, equation (1).

\[
\begin{align*}
I_r &= \frac{Z_{lb}}{Z_{lb} + (Z_m + Z_p)} I_M \\
I_i &= \frac{Z_{lb}}{Z_{lb} + (Z_m + Z_p)} I_N
\end{align*}
\]

(1)

Where, $Z_{lb}$ is the impedance of the dc filtering link; $Z_m$ is the impedance of the converter; $Z_p$ is the impedance of the flat-wave reactor; $I_M$ is the detection value of the current detection point on the rectifying side; $I_N$ is the detection value of the inverter current detection point.

As can be seen from 1.2, the impedance amplitude of the dc filter $Z_{lb}$ is close to 0 at 600Hz. According to formula (1), the flat-wave reactance branch current on both sides of the transmission line is close to 0. At this point, the dc filter branch is close to the state of short circuit.

3.2. External fault

If external fault occurs in the positive pole line, take the lateral fault of the rectifying side flat-wave reactor as an example to analyze, and its fault network is shown in figure 3.

![Figure 3. Fault component network for external fault](image)

We still consider the dc filter bank branch as a short circuit. According to the shunt relationship, the flat-wave reactance branch currents on the rectifying side and the inverting side $I_r$ meet the following equation (2).

\[
I_r = \left(1 - \frac{Z_m}{Z_m + Z_p}\right) \frac{U_M}{R_f}
\]

(2)

Where $U_M$ is the measured value of voltage detection point on the rectifying side; $R_f$ is excessive resistance.

Taking Yunguang ± 800kV DC transmission line as an example, the value of excess resistance $R_f$ is generally about 5-500Ω; The impedance of the converter $Z_m$ is about 1000Ω when the harmonic current is 600Hz, and that of the flat-wave inductive reactor is 400Mh [11, 12].

The calculation shows that $I_r$ is different from the internal fault, it is obviously greater than 0. It is obviously different from the fault in the region and verifies the feasibility of the fault criterion internal fault and external fault.

Similarly, it can be found that the flat-wave reactance branch current near the inverter side $I_i$ has the same characteristics when the fault is external fault.
4. Protection scheme

4.1. S transform
To realize the above protection logic, the 600Hz current component in the fault current should be extracted first. In this paper, S transform [13, 14] is used to obtain the current information required by the scheme. For the current signal $i(t)$, the Fourier transform is first calculated, and then its S transform expression can be deduced, which can be obtained as follows:

$$
S(\tau, f) = \int_{-\infty}^{+\infty} i(t) \frac{|f|}{\sqrt{2\pi}} e^{-\frac{|f-t|^2}{2}} e^{-j2\pi \tau} dt
$$

(3)

Where $f$ is frequency and $\tau$ is the central value.

Based on the S transformation of current $i(t)$, its discrete form can be deduced as follows:

$$
S[kT, \frac{n}{N_T}] = \sum_{n=0}^{N_s-1} \left[ \frac{m+n}{N_T} \right] e^{\frac{j\pi m}{N_s}} e^{\frac{j2\pi n}{N_s}}
$$

(4)

$$
S[kT, 0] = \frac{1}{N_s} \sum_{n=0}^{N_s-1} \left[ \frac{m}{N_T} \right]
$$

Where, $i[kT]$ $(k = 0, 1, \cdots, N_s - 1)$ is the discrete time series of continuous current signal $i(t)$, and $T$ is the sampling interval;

$m$ and $n$ are discrete frequency points; The $I \left[ \frac{m+n}{N_T} \right]$ is Fourier transform of $i[kT]$.

4.2. The criterion of external fault & internal fault
In this paper, the fault in or out of the HVDC line is identified by the current of the flat-wave reactance branch near the inverter or rectifying side branch in the HVDC dc filter link. And as a criterion.

Calculate the average value of $I_r$ and $I_i$ in this period, and get:

$$
\begin{align*}
\bar{T}_r & = \frac{1}{n_x} \sum_{i=1}^{n_x} I_r(i) \\
\bar{T}_i & = \frac{1}{n_x} \sum_{i=1}^{n_x} I_i(i) \quad i \in N
\end{align*}
$$

(5)

Where, $n_x$ is the number of sampling points in the sampling time window; $I_r(i)$ is the current value corresponding to the $i$ point of the rectifying side flat-wave reactance branch; $I_i(i)$ is the current value corresponding to $i$ point of the inverting side flat-wave reactance branch.

When the fault occurs in the region, the current of the flat-wave reactance branch on the rectifying side and the inverting side is close to 0. Considering the impedance and engineering error margin of the dc filter branch, its value should be less than a certain value $I_{\text{set}}$. When out-of-zone fault occurs, the flat-wave reactance branch current at the fault end should be much larger than the a certain value $I_{\text{set}}$. Thus the fault identification criterion described in this paper is constituted. The criterion formula is as follows:

$$
J = \max \left( \bar{T}_r, \bar{T}_i \right) < I_{\text{set}}
$$

(6)
The threshold $J_{\text{set}}$ value is determined by the dc filter impedance and engineering margin of the specific line, and it should be less than the minimum value of the flat-wave reactance branch current of the rectifying side and the inverting side when the fault occurs. In this paper, one-fifth of the current value of the rectifying side and the inverting side of the flat-wave reactance branch at the time of fault is selected to ensure reliable judgment.

$$J_{\text{set}} = \left(1 - \frac{Z_m}{Z_m + Z_p}\right)\frac{U_M}{5R_f}$$  \hspace{1cm} (7)

Combined with the data in 2.2, the threshold value $J_{\text{set}} = 40$ was selected in this paper. If equation (7) is true, it is judged as internal fault, otherwise it is internal fault.

4.3. Start the criterion
When line running normally, busbar current basic stable, and the voltage current testing point M, N $I_M$ and $I_N$ will have a very sharp rise or fall, at this time as long as the monitoring of the current waveform (hereinafter mentioned are all on the time domain waveform) on the average of the slope can protect the start-up criterion, specific criterion is as follows:

$$D_M = \frac{1}{n_s} \sum_{i=1}^{n_s} \left(\frac{dI_M(i)}{dt}\right)$$
$$D_N = \frac{1}{n_s} \sum_{i=1}^{n_s} \left(\frac{dI_N(i)}{dt}\right)$$  \hspace{1cm} (8)

$D_{\text{set}}$ is the threshold value of startup, Select $D_{\text{set}}$ according to the impedance characteristics of the line. Compare with $D_{\text{set}}$, the larger of $D_M$ and $D_N$, and the startup criterion can be obtained.

$$D = \max(D_M, D_N) > D_{\text{set}}$$  \hspace{1cm} (9)

By a [15] the ±800kV line of short circuit the short circuit current is not lower than 1.6 kA/ms, so generally preferable =. In order to prevent the fluctuations caused by lightning, this scheme also introduces image stabilization criterion, namely 3ms judge again, if two adjacent to judge different judgment is invalid, until they get the two adjacent judgment is a failure, just start.

4.4. Selection Pole criteria
In the bipolar HVDC system, the slope of current waveform is similar when the fault occurs. In the case of unipolar fault, the slope of non-fault current waveform is less than the fault level. Thus, the proportional coefficient of positive and negative poles can be obtained $P$:

$$P = \frac{\sum_{i=1}^{n_s} \left(\frac{dI_{160}(i)}{dt}\right)}{\sum_{i=1}^{n_s} \left(\frac{dI_M(i)}{dt}\right)}$$  \hspace{1cm} (10)

This constitutes the criterion:
Where, $P_{set1}$ and $P_{set2}$ are the threshold values of fault selection criterion. Generally speaking, the coupling coefficient between bipolar transmission lines is less than 0.5[16]. Considering the high resistance grounding and the exhaustion of long distance lines, a certain margin is retained. $P_{set1}=1.4$ and $P_{set2}=0.6$ were selected in this paper.

4.5. Protection logic
See figure 4 below. First extract data first, if meet the stabilization treatment of start-up criterion (9), extracted by S transformation flat wave reactance of harmonic current in the branch of the current information in 600Hz, if meet the type (6), depending on the type (9) are negative ratio value, on the basis of type (10) and then choose a judgment, finally the corresponding protection action. If equation (6) is not satisfied, the fault occurs outside the zone and protection returns.

![Figure 4. Flow chart of protection](image)

5. Simulation verification and analysis
PSCAD/EMTDC software was used to build the simulation model of ±800kV bipolar HVDC dc project, with power transmission of 6000MW and line length of 2000km. 2/12/39 three-tone dc filters are installed at both ends of the dc line. The sampling frequency was 10kHz.

5.1. Steady state operation and fault start
Assume that an in-zone fault occurs in 5s. Figure 5 shows the change of the startup function before and after the fault.
Figure 5 shows the data window (4.98s~5.05s), indicating that the current at the detection points M and N rises rapidly after the fault. Therefore, after a delay of 4ms, the value of the startup function D rises rapidly and exceeds the set value given by the criterion, and the startup criterion takes effect.

5.2. Internal fault

Figure 6 shows the change of the selected function value before and after the fault.

The data window shown in figure 6 (4.98s~5.015s) shows that, after the fault occurs, most of the 600Hz harmonics flow into the earth through the dc filter, and the flat-wave reactance branches on the rectifying side and the inverting side have almost no 600Hz harmonics. The value of the selection function is far less than the set value of 40, so it is judged as internal fault.

5.2.1. Select Pole. FIG. 7 shows the change of P value of the grading function before and after the occurrence of three pole-selecting possibilities
The three sections in figure 7 represent the positive, negative, and bipolar faults in turn. From the figure, we can clearly see the relationship between the upper and lower limits. It indicates the successful operation of the criterion.

5.3. External fault

Figure 10 shows the change of the value J of the selected function before and after the fault.

Figure 7. The change of the select pole function

Figure 8. The change of the select area function before and after the fault 2
The data window shown in figure 10 (4.98s~5.015s) shows that the harmonic current of 600Hz is flowing through the flat-wave reactance branch on the rectifying side and the inverting side between the flat-wave reactor and the converter station because the fault point occurs. Therefore, the value of the selected function J is far greater than the set value of 40, so it is judged as an out-of-zone fault.

6. Conclusion
Based on the current characteristics of HVDC flat-wave reactance branch, a fault identification scheme based on current variation is proposed in this paper. Theoretical and simulation experiments show that:

(1) When it is internal fault, the current value of the flat-wave reactance branch on the rectifying side and the inverting side is close to 0; When it is external fault, the current value of the rectifying or inverting side of the flat-wave reactance branch is much greater than 0. The fault can be identified by this criterion.

(2) The scheme adopted in this paper only needs to read the electricity volume and the current data of the detection point and the impedance branch current, and can accurately identify faults by calculating the change of the current, and it has a good ability to withstand excessive resistance, with low communication requirements. Enhance the safety of HVDC line.

(3) The principle is simple, the calculation amount is small, and under various working conditions can quickly and effectively identify the fault inside and outside the zone, to complete fault selection.

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