Longitudinal Protection of LCC-VSC Bipolar HVDC Transmission Line Based on Model Identification and Current Polarity

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Abstract. For hybrid bipolar DC transmission systems, combined with model identification and current polarity, a new principle of longitudinal protection of transmission lines is proposed. This paper analyzes the fault network and finds: when the front end of the inverter side fails, the fault model is equivalent to the C model, and when the back side of the inverter side fails, the fault model is equivalent to the RL model; when the front end of the rectification side fails, the rectification side fault current has a positive polarity, and when the rectification side back side fails, the rectification side fault current has a negative polarity. In conclusion, DC line area failure, namely the inverter side front and rectifier side front fault at the same time, the fault model matching C model, there was a positive polarity fault current at the same time; Failure occurs outside the DC line area, namely the inverter side front and rectifier side front no fault at the same time, inverter side failure model does not match the C model, or rectifier side fault current with a negative polarity. This new principle compensates for primary protection and can be used as an improvement to backup protection.

1. Introduction

The phase-controlled converter-type direct current (LCC-HVDC) transmission technology has many drawbacks. For example, the problem of commutation failure is inevitable, and a large amount of reactive power compensation is required, and it cannot work under the extremely weak AC system of the receiving end. The voltage source type direct current transmission (VSC-HVDC) based on the fully controlled device compensates for the defects of the LCC-HVDC, but there are also disadvantages. Combining LCC and VSC HVDC transmission technology can complement each other and maximize the advantages of both. Therefore, hybrid research on DC transmission has become a hot issue.

Literature [1-2] proves that the key component of HVDC transmission technology is the line. Therefore, studying its protection principle is of great value. It can be known from the literature [3] that the traveling wave protection method has always occupied a large proportion in the line protection, but the anti-interference and reliability are poor. The protection principle of parameter identification proposed in literature [4] shows advantages in reliability and quick movement. Literature [5] applies parameter identification in the frequency domain, while literature [6] applies parameter identification in the time domain. In general, the higher level of parameter identification problem of complex, lower
movement speed then. To solve this problem, the protection of the principle of pattern recognition can solve [7-10], it transforms the problem of fault diagnosis into a comparison problem of model error.

In this paper, the LCC-VSC bipolar system is used as the analysis object. Combined with the model identification and current polarity, a new longitudinal protection principle of LCC-VSC bipolar line based on model identification and current polarity is proposed.

2. LCC - VSC bipolar HVDC system structure

The structure of the LCC-VSC bipolar hybrid HVDC system is shown in figure 1. The left and right ends are the rectifier station and the inverter station, which are denoted as the M side and the N side, respectively. Such wiring shown in figure 1 is applied to a high voltage, large capacity and high reliability transmission conditions [11]. The positive and negative poles of the VSC side are connected in parallel with a large capacitor.

![Figure 1. Bipolar hybrid DC transmission system.](image1)

In figure 1, G and Z_s represent the equivalent AC system and system impedance. Wherein, subscript 1 represents the rectification side, and subscript 2 represents the inverter side; i_M and u_M represent the current and voltage of the rectifier, i_N and u_N represent the current and voltage of the inverter side. Wherein, the subscript p represents the positive pole, and the subscript n represents the negative pole; f indicates where the fault occurred. Wherein, the subscript 1 represents the inside of the DC transmission line, the subscript 2 represents the outside of the rectifying side flat-wave reactor, and the subscript 3 represents the outside of the inverter side capacitor. The reference direction is shown in figure 1.

3. Fault Characteristics Analysis of LCC-VSC HVDC Line

3.1. External fault of the DC line

The network with a line external fault on the N side and M side of the DC line is shown in figure 2 and figure 3. u_e is the fault voltage source, i_i is the fault current, and C_p is the large capacitor; L, R, C are the equivalent parameters of the line, R_i and L_s are the equivalent impedance parameters of the system. Among them, the subscripts M and N represent the rectifier side and the inverter side. The line π model is adopted. The current reference direction is indicated in the figure.

![Figure 2. N-side external fault additional network.](image2)

![Figure 3. M-side external fault additional network.](image3)
3.1.1. **DC line external fault on the N side.** As shown in figure 2 above, when a fault occurs outside the N-side capacitor, on the M side, the rectifier side fault current has a positive polarity due to the fault voltage source [12]. Then there are:

\[ \Delta i_M > 0 \]  

On the N side, there is:

\[ \Delta u_N = (R_M + R)\Delta i_N + (L_M + L) \frac{d\Delta i_N}{dt} \]  

Equation (2) can be explained that by using the single-ended amount on the N side, the N-side external fault model can be equivalent to the C model.

3.1.2. **DC line external fault on the M side.** As shown in figure 3 above. When a fault occurs outside the flat-wave reactor on the M side, for the M side, the rectifier side fault current has a negative polarity due to the fault voltage source. Then there are:

\[ \Delta i_M < 0 \]  

On the N side, the converter shunt \( \Delta i_{sM} \) and the line reactance shunt \( \Delta i_{cN} \) are ignored. It follows that:

\[ -\Delta i_N = C_p \frac{d\Delta u_N}{dt} \]  

Equation (4) can be explained that by using the single-ended amount on the N side, the M-side external fault model can be equivalent to the C model.

3.2. **DC line internal fault**

The fault network diagram in the transmission line area in Figure 1 is shown in Figure 4.

![Figure 4. Additional network for internal line faults.](image)

On the M side, the rectifier side fault current has a positive polarity due to the fault voltage source. which is:

\[ \Delta i_M > 0 \]  

On the N side, there is:

\[ -\Delta i_N = C_p \frac{d\Delta u_N}{dt} \]  

Equation (6) can show that the line internal fault model can be equivalent to the C model.

4. **Protection principle and criteria**

4.1. **Model identification protection principle and criteria**

It can be seen from the analysis in Section 2 that using the single-ended quantity on the N side, the fault model of the M side external and the internal line can be equivalent to the C model; the N side external fault model is equivalent to the RL model. To distinguish between the two models, define the capacitance model error function as follows:
In equation (7): \( T = 10\text{ms} \).
The construction protection criteria are as follows:

\[
E_C < \mu_{\text{set}}
\]  

In equation (8): \( \mu_{\text{set}} \) is the capacitance model error setting value.

### 4.2. Protection principle and criterion using current polarity

It can be seen from the analysis in Section 2 that using the fault current symbol on the M side, it can be known that \( \Delta i_M < 0 \) on the M side external fault; \( \Delta i_M > 0 \) in the line internal fault and the N side external fault. Thus, a fault current average function is constructed to reflect the polarity of the fault current.

The function of defining the fault current average is as follows:

\[
i = \frac{1}{N} \int_{0}^{T} \Delta i \, dt
\]

In equation (9): \( T = 10\text{ms} \), where \( N \) is the corresponding number of sampling points.

Construction protection criterion is as follows:

\[
\frac{1}{N} \int_{0}^{T} \Delta i \, dt > k \cdot I_{\text{set}}
\]

In equation (10): \( T = 10\text{ms} \), \( N \) is the corresponding number of sampling points. \( k \) is the reliability factor, 1.2~1.5 is acceptable; \( I_{\text{set}} = 0.1 \cdot I_n \), \( I_n \) is the rated current value of the DC system.

### 4.3. Protection criteria implementation method

According to the analysis in sections 4.1 and 4.2, the capacitance model starts when the error is less than the threshold value, and starts when the current mutation component is greater than the threshold value. The constructor is as follows:

\[
F(A, B) = A \land B
\]

\[
A = \text{sign}(\mu_{\text{set}} - E_C)
\]

\[
B = \text{sign}\left(\frac{1}{N} \int_{0}^{T} \Delta i \, dt - k \cdot I_{\text{set}}\right)
\]

In equation (12) and equation (13): \( \text{sign}(\bullet) \) is a sign function, when \((\bullet) > 0\), \( \text{sign}(\bullet) = 1 \); when \((\bullet) < 0\), \( \text{sign}(\bullet) = 0 \). \( T = 10\text{ms} \), where \( N \) is the corresponding number of sampling points.

It can be seen that when \( F(A, B) = 1 \), the capacitance model error is small at this time, the polarity of the rectifier side fault current is positive, and it is judged as the internal fault of the line; when \( F(A, B) = 0 \), it is judged as the external fault of the line.

### 5. Current polarity and model identification longitudinal protection strategy

When the capacitance model error is large, it is determined as the back-side fault on the N side, and the fault occurs outside the HVDC transmission line. At this point, the N side does not need to send fault signals to the M side. Only when the fault occurs in front of the N side, i.e. the capacitance model error is small, will the fault signal be sent to the M end, and the capacitor model error discriminating element on the inverter side is started.
When the fault occurs behind side M, the fault current at side M has negative polarity, i.e. \( \Delta i_M < 0 \). At this time, it is not necessary to start the discriminating element of current polarity. The discriminating element is activated only when the fault occurs in front of the M side, that is, \( \Delta i_M > 0 \).

In short, only when the current polarity discriminating element on the M side is activated and the feedback of the N side capacitive model error discriminating element acti, it can be known that the fault occurs inside the DC line, the protection device operates, and the reliability is relatively high. The logic diagram of the longitudinal protection action is shown in figure 5.

**Figure 5.** Principle of longitudinal protection.

As can be seen from figure 5, the protection device transmits an action command only when the two-stage converter station discriminating elements operate.

### 6. Simulation

The simulation model of the 500 kV LCC-VSC hybrid bipolar HVDC system is shown in figure 1. The rated current is 2 kA and the total length of the DC line is 1000 km. The capacitance of the positive and negative poles in parallel on the VSC side is 1000 \( \mu \)F, and the data acquisition frequency is 10kHz. The fault occurred at 1.85 s and lasted for 0.1 s. The data window takes 10ms and the sliding window takes 20ms. To ensure reliability, \( \mu_{set} \) is taken as 0.5.

#### 6.1. DC line external fault simulation results

**6.1.1. DC line external fault simulation results on the N side.** When a metallic grounding occurs outside the capacitor on the N side, the fault simulation diagram is shown in figure 6. (corresponding to \( f_2 \) in figure 1)

As can be seen from figure 6, the outside of the DC line on the N side is faulty. Within 5 ms~15 ms after the fault, the calculated average value of the rectifier side fault current is greater than the set value \( k \cdot I_{set} \), but the error value of the inverter side capacitor model is greater than the set value \( \mu_{set} \).

At this time, the current polarity discriminating element is activated, but the capacitance model discriminating element is not activated. It is judged to be an external fault of the DC line and the protection device is not activated.
6.1.2. DC line external fault simulation results on the M side. When metal grounding occurs outside the flat-wave reactor on the M side, the fault simulation diagram is shown in figure 7. (corresponding to $f_3$ in figure 1)

![Figure 7. Metal ground fault occurs outside the M side.](image)

As can be seen from figure 7, the outside of the DC line on the M side is faulty. Within 5 ms~15 ms after the fault, the calculated error value of the inverter side capacitor model is less than the set value $\mu_{set}$, but the average value of the rectifier side fault current is less than the set value $k*I_{set}$ at this time, the capacitance model discriminating element is activated, but the current polarity discriminating element is not activated, so it is determined that the external fault of the DC line does not activate the protection device.

6.2. DC line internal fault simulation results
When a metal ground is generated at a position closer to the N side inside the DC line, the fault simulation diagram is shown in figure 8: When the high-resistance grounding occurs at a position closer to the M side, the fault simulation diagram is shown in figure 9. (corresponding to $f_1$ in figure 1)

![Figure 8. Metal grounding 50 km from the N end.](image)

![Figure 9. Grounded through a 500 $\Omega$ transition resistor at 50km from the M end.](image)

It can be seen from figure 8 to figure 9 that different ground faults occur at different positions inside the DC line. Within 5ms to 15ms after the fault occurs, the calculated average value of the rectifier side fault current is greater than the set value $k*I_{set}$, and the capacitance model error value on the inverter side is less than the set value $\mu_{set}$. At this time, the current polarity discriminating element is activated, and the capacitance model discriminating element is also activated. It is determined that the internal fault of the line and the protection device is activated.
It can be seen from the above simulation that the simulation results of the capacitance model discriminating element on the inverter side and the current polarity discriminating element on the rectifying side are consistent with the theoretical analysis.

7. Conclusion
Aiming at the LCC-VSC hybrid bipolar DC transmission system, a new principle of longitudinal protection for DC transmission lines based on model identification and current polarity is proposed. Analysis and simulation show that this principle can respond to faults 5 to 15ms after a fault, without filtering, resistance to transition resistance, simple and easy adjustment. It can compensate for the primary protection or it can be used as an improvement to the backup protection.

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References
[1] Zhao Yuejiao. Fault detection of HVDC transmission line based on improved Blackman window [D]. Northeast Petroleum University, 2018.
[2] Zhai Xingfu, Song Guobing, Xu Haiyang, et al. New Principle of Pilot Protection for VSC-HVDC Transmission Lines Using Modulus Model Identification[J]. Automation of Electric Power Systems, 2014, (10): 100-106.
[3] Qi Guoqiang, Wang Zengping. Hilbert-Huang Transform Based HVDC Mutation Direction Pilot Protection Method[J]. Power System Protection and Control, 2017, 45(20): 92-99.
[4] Suo Nanjiale, Kang Xiaoning, Song Guobing, et al. Preliminary study on the principle of relay protection based on parameter identification[J]. Journal of Electric Power System and Automation, 2007, 19(1): 14-20, 27.
[5] Yang Lijun, Peng Pan, Gao Wei, et al. Interval identification of moisture and aging of oil-paper insulation based on frequency domain dielectric response signature fingerprints[J]. Transactions of China Electrotechnical Society, 2018, 33(9): 2105-2114.
[6] Hou Junjie, Fan Yanfang, Wang Yibo. Research on Time Domain Distance Protection of Parameter Identification for Cluster Wind Power Transmission Line[J]. Power System Protection and Control, 2018, 46(5): 46-53.
[7] SONG Guobing, YAN Xingfu, LI Dekun, et al. Vertical protection of voltage source converter type DC transmission line for identifying model parameters[J]. Journal of Xi’an Jiaotong University, 2013, 47(8): 110-114.
[8] Zhai Xingfu, Wu Xiaoming, Zheng Jiafa, Zhang Jinfeng, Zhu Can. Longitudinal Protection of HVDC Transmission Lines Based on Model Identification[J]. Electric Power Survey and Design, 2017(S2): 202-206+335.
[9] SONG Guobing, YAN Xingfu, YAN Mengbing, et al. Pilot protection of VSC-HVDC transmission line based on parallel capacitance parameter identification[J]. Automation of Electric Power Systems, 2013, 37(15): 76-82, 102.
[10] Yuan Hailong, Yuan Yuan, Song Hailian. A new method for longitudinal protection of HVDC transmission lines [C]. //2013 Proceedings of the Annual Meeting of China Electrical Engineering Society. 2013: 1-6.
[11] Zhao Chengyong, Guo Chunyi, Liu Wenjing. Mixed DC Transmission [M]. 2014
[12] Gao Shuping, Sonan Jiale, Song Guobing, et al. New Principle of Longitudinal Protection of HVDC Transmission Lines Using Current Mutation Characteristics[J]. Automation of Electric Power Systems, 2011, 35(5): 52-56, 86.