A New Protection Principle of Hybrid Bipolar HVDC Line Based on Voltage Fault Component Rate of Change

ZHU Hangjian\textsuperscript{1*}, GAO Shuping\textsuperscript{1}, FU Zhouxing\textsuperscript{1}

\textsuperscript{1}College of Electrical and Control Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi, XiAn, SN 29, China
\textsuperscript{*}Corresponding author’s e-mail: 568569726@qq.com

Abstract. At present, hybrid HVDC transmission has become a research hotspot. In this paper, the fault-added state characteristics of the hybrid bipolar HVDC transmission system with different faults on the DC transmission line are analyzed by connecting small inductors on both sides of the HVDC transmission line. A single-ended quantity protection method using voltage transient components is obtained. By analyzing the rate of change of voltage fault component, the transient energy component is used to calculate the instantaneous energy magnitude of the transient voltage component to distinguish the fault in the region. The energy function is constructed by the transient voltage of the positive and negative rectifiers to fault selection. The simulation results verify the correctness of the proposed protection principle and can achieve fault pole selection.

1. Introduction
In the protection of HVDC transmission lines, domestic and foreign scholars have carried out a lot of research work and obtained some meaningful research results. In [1], based on the characteristics of current waveforms at specific frequencies at both ends, a new protection scheme for DC transmission line longitudinal protection is proposed. Literature [2] proposed the possible influence of nonlinear line boundary on boundary protection, and the high-resistance fault may be invalid for traveling wave detection. Literature [3] analyzed the construction of time domain current differential protection under the distributed parameter model. In [4], several factors affecting the traveling wave characteristics such as the distribution parameter fault location and transition resistance are analyzed. In [5], a method for protection of UHVDC transmission lines based on phase-mode transformation is studied. In [6], a protection strategy for high-voltage DC transmission lines using directional characteristics of voltage and current abrupt changes is proposed.

In this paper, the faults in the positive and negative regions, the faults in the negative region, the bipolar faults, etc. are analyzed. The fault additional state of the hybrid bipolar DC transmission system is analyzed. According to the difference between the rate of change of the voltage fault component in the fault outside the region, a new protection principle using the voltage fault component is proposed. And use the energy function of the transient current to achieve fault selection. Combined with the actual DC transmission project, due to the limitation of the converter of the two-level flexible DC transmission system, a hybrid bipolar DC transmission system with positive $+500\text{kV}$ and negative-$200\text{kV}$ was built in the PSCAD electromagnetic transient simulation software, and MATLAB was used algorithm verification.
2. Topology of hybrid bipolar HVDC transmission system
The structure and fault setting of the hybrid bipolar HVDC transmission system are shown in Figure 1.

![Figure 1. Hybrid Bipolar DC Transmission System Structure](image)

F1 is the ground fault in the positive region; f2 is the ground fault in the negative region; f3 is the ground fault outside the positive rectifier side, f4 is the ground fault outside the positive inverter side region, f5 is the positive and negative pole bipolar ground fault, f6 is Positive and negative bipolar short circuit failure.

Table 1 gives the parameters for the Hybrid Bipolar-HVDC system.

| Transformer (MVA) | Flat wave reactor (H) | DC capacitor (μF) |
|------------------|-----------------------|------------------|
| LCC Rectification side | 345/213, 603.73 | 0.5968 / |
| Inverter side | 209/230, 603.73 | 0.5968 / |
| VSC Rectification side | 345/115, 603.73 | / 2000 |
| Inverter side | 115/230, 603.73 | / 2000 |

3. Analysis of Failure Rate of Faulty Network Voltage Faults and Fault Criterion in and Out of Area
The fault additional state is shown in Figure 2.

![Figure 2. Fault state network diagram](image)

As shown in Fig. 2(a), the fault in the positive electrode region is shown. When a fault occurs, the voltage fault components upr1 and up1 fall at a high rate. Due to the presence of series inductance,
the current flowing through the inductor increases rapidly, causing an inductor voltage, and the voltage fault components upr2 and upi2 fall at a much lower rate.

As shown in Fig. 2(c), there is a fault outside the positive electrode region (rectifying side). When a fault occurs, the rate of the voltage fault component upr2 drops rapidly. Due to the presence of the series inductance, the current flowing through the inductor increases rapidly, which induces an inductor voltage, and the voltage fault component, upr1, upi1 and upi2, are much slower.

The fault in the zone is exemplified by fault f1; the analysis process of faults f2, f5, and f6 is similar to fault f1 and the analysis result is the same as fault f1. The out-of-zone fault is exemplified by fault f3; the analysis process of fault f4 is similar to fault f3 and the analysis result is the same as fault f3.

Therefore, this paper uses the Teager energy operator to find the instantaneous energy of the voltage fault component upr1 and the voltage fault component unr1 on the right side of the rectifier side series inductor to distinguish the faults inside and outside the zone. The instantaneous energy of the voltage fault component upr1 and the voltage fault component unr1 is S. When a fault occurs in the positive electrode region, the instantaneous energy of the voltage fault component upr1 is large; when a fault outside the positive region occurs, the instantaneous energy of the voltage fault component upr1 is small. When a fault occurs in the negative region, the instantaneous energy of the voltage fault component unr1 is large; when an external fault occurs in the negative region, the instantaneous energy of the voltage fault component unr1 is small.

Therefore, the setting value of the instantaneous energy can be set. When S>Sset, it is an intra-region fault, and when S<Sset, it is an out-of-zone fault. The instantaneous energy setting Sset is a threshold set according to the maximum instantaneous energy value under the obstacle outside the zone, Sset=100.

4. Fault pole selection
The amount of change in the voltage fault component on the fault pole is far greater than the amount of change in the voltage fault component on the healthy pole. Therefore, the voltage fault component upr1 on the positive rectifier side and the voltage fault component unr1 on the negative rectifier side are integrated and configured as energies E1 and E2, respectively, as in equations (1) and (2):

$$E1 = \sum_{i=1}^{N} |u_{pr1}|^2$$

$$E2 = \sum_{i=1}^{N} |u_{nr1}|^2$$

In the formula, upr1 and unr1 are respectively the voltage fault component of the positive rectifier side and the voltage fault component of the negative rectifier side; E1 and E2 are the energy of the positive and negative poles respectively; N is the number of sampling points.

The energy at the fault pole is greater than the energy at the health pole, so the threshold value Eset is set. When E1>Eset, the positive pole fails; when E2>Eset, the negative pole fails; when E1>Eset and E2>Eset, double pole faulty occurs. Eset=1×10^6.

5. Simulation
5.1. Zone fault simulation verification
Due to the limitation of space, the fault simulation result in the area takes the fault f1 as an example. The simulation result of fault f1 is shown in Fig. 3.
In summary, \( S > S_{\text{set}} \), \( E_1 = 6 \times 10^7 > E_{\text{set}} \), so fault f1 is a fault in the positive region.

5.2. Out-of-zone fault simulation verification

Due to the limitation of space, the simulation result of the out-of-zone fault takes the fault f3 as an example. The simulation result of fault f3 is shown in Fig.4.

In summary, \( S < S_{\text{set}} \), so fault f3 is an out-of-zone fault. Since the fault f3 is an out-of-zone fault, it is not necessary to judge the fault pole.

6. In conclusion

Hybrid DC transmission has become a hot topic in current research. This paper establishes a model for hybrid bipolar HVDC transmission in PSCAD software, and analyzes the principle of relay protection of its line as follows.

(1) The fault characteristics of the hybrid bipolar DC transmission system are analyzed by connecting small inductors on both sides of the DC transmission line. The difference between the transient voltage component conversion rates on both sides of the series inductance is derived from the DC line protection principle in the region based on the instantaneous energy of the voltage fault component.
(2) By using the Teager energy operator to extract the instantaneous energy of the transient voltage component, when an area fault occurs, $S > S_{set}$; when an out-of-zone fault occurs, $S < S_{set}$.

(3) The fault pole is judged by constructing energy for the transient voltage of the positive pole and negative pole rectifier sides.

The simulation results show that the protection principle can quickly identify faults in the hybrid bipolar HVDC transmission system with high reliability.

Acknowledgments
This work was supported by the National Natural Science Foundation of China under Grant No.51777166.

References
[1] Liu Jian, Geng Duling, Fan Chunju. Pilot protection of HVDC transmission lines based on current waveform matching[J]. Power System Technology, 2015, 39(06): 1736-1743
[2] Yu Yang, Sun Xuefeng, Gao Peng, Liu Xinghua, Chen Yongqiang, Liu Lin. Transient protection analysis and prospect of HVDC transmission lines[J]. Power System Protection and Control, 2015, 43(02): 148-154
[3] Liu Qi, Song Guobing. The current differential protection of HVDC transmission lines using time-domain waveform comparison[J]. Automation of Electric Power Systems, 2015, 39(24): 87-95
[4] GAO Ben-feng, LIU Xinye, ZHANG Yunxiao, ZHAO Shuqiang, MA Yulong. Travelling Wave Characteristics and Setting of Protection Settings for HVDC Transmission Lines[J]. Automation of Electric Power Systems, 2015, 39(16): 120-125
[5] Bingbing. Research on rapid protection of UHV DC transmission lines [D]. Shandong University, 2014.
[6] Xing Luhua, Chen Qing, Gao Zhanjun. The principle of line protection for HVDC transmission based on the direction of abrupt changes in voltage and current[J]. Automation of Electric Power Systems, 2013, 37(06): 107-113