A novel protection scheme for VSC-HVDC transmission lines based on current integral autocorrelation

Chuanjian Wu | Dahai Zhang | Guomin Luo | Meng Li | Jinghan He

School of Electrical Engineering, Beijing Jiaotong University, Beijing, People’s Republic of China

Correspondence
Dahai Zhang, School of Electrical Engineering, Beijing Jiaotong University, Beijing, People’s Republic of China.
Email: dhzhang1@bjtu.edu.cn

Funding information
National Key R&D Program of China, Grant/Award Number: 2018YFB0904600; State Grid Corporation Technology, Grant/Award Number: 5200-201956113A-0-0-00

Abstract
Voltage source converter-based high voltage direct current (VSC-HVDC) transmission system has become the mainstream of power construction and plays an increasingly important role in the power system. However, the DC line fault results in shutting down of the converters, which can greatly endanger the security of the power grid. So it is essential to find a fast fault identification strategy for DC line protection technology. In addition, the existing backup protection scheme has the problems of long delay and strict communication synchronisation requirements. Therefore, this study proposes a novel protection scheme for VSC-HVDC transmission lines based on the fault current integral autocorrelation coefficient. The fault current and fault current frequency characteristics of VSC-HVDC transmission lines are analysed first. Second, this study proposes a method to filter out distributed capacitance current by current integration and eliminate the oscillation of fault current. Finally, the difference of the current integral during different faults (internal or external fault) is analysed, and the autocorrelation coefficient is introduced to express the difference. Hence, this study proposes a new principle for identifying faults using the autocorrelation coefficient of the fault current integral. Simulation results show that the protection principle is not affected by the distributed capacitive current and does not require strict communication synchronisation. It has an excellent performance in intolerance to fault resistance and noise interference and can be used as backup protection for VSC-HVDC transmission system.

1 | INTRODUCTION

Voltage source converter-based high voltage direct current (VSC-HVDC) has great advantages in solving new energy grid connections, central load power supply, and regional grid interconnection. Building a VSC-HVDC grid based on existing VSC-HVDC projects has also become a future trend [1–3]. However, when the VSC-HVDC transmission line faults, if the protection cannot be activated quickly, the converter will be severely damaged. To address this problem, protection schemes that can quickly and accurately identify faults should be proposed [4–6]. Moreover, the fault current of the DC line has a fast-rising rate, and the components in the converter have a weak ability to withstand the inrush current. Therefore, the power grid requires that the fault identification and protection actions be completed within milliseconds. At the same time, the protection scheme must also consider the effects of line distributed capacitance, high transition resistance, and communication errors.

In the current research, the protection principle can be divided into two types: Protection based on either single-ended or double-ended signals. Travelling wave protection, which is single-ended quantity protection, is easily affected by high resistance grounding, although it has a shorter action time and is not affected by distributed capacitance [7]. The authors in [8, 9] studied current and voltage differential protections, respectively. Those studies use the wavelet transform coefficient and differential of current or voltage to constitute fault criteria. However, due to the lack of obvious boundaries of VSC-HVDC transmission lines, the above-mentioned protection schemes relying on single-ended electrical quantities are not be applied directly for multi-terminal DC grids [10, 11].
The protection scheme that is based on double-ended signal is mostly differential protection, and it has obvious boundaries and little affected by high transition resistance. But it is easily affected by the distributed capacitance current of the line. To solve the problem in which the pilot protection is affected by the distributed capacitance of the line, differential protection that compensates the distributed capacitance current was proposed in [12, 13]. However, the scheme for compensating distributed capacitance is complicated, and there are difficulties in application. Due to travelling wave fault information and after considering distributed capacitators, [14] proposes a differential protection scheme based on two sections of the travelling waves.

Since the traditional protection algorithm still has some problems that are difficult to solve, some scholars introduce the concept of correlation and expect to study a new type of protection principle. In [15], a protection scheme using the correlation of travelling waves is proposed. However, it is affected by line attenuation, chromatic dispersion, refraction and reflection and has the disadvantages of a large amount of calculation, heavy communication burden, difficult detection, and low reliability. In [16], a protection principle based on transient current correlation is proposed. The above-mentioned correlation protection principle is fully applicable to DC distribution systems. However, the VSC-HVDC transmission system has the characteristics of long lines and high requirements for operation time. Since the influence of distributed capacitance is not eliminated by the protection principle based on transient current correlation, the long line characteristics of VSC-HVDC transmission may cause a large delay in the protection principle based on transient current. At this time, the rapidity of the protection of the VSC-HVDC transmission grid cannot be guaranteed. Besides, communication is an inevitable issue for VSC-HVDC protection. The above-mentioned correlation-based protection principle requires a large number of signals to be transmitted to the opposite end, which increases the burden of communication.

So the following challenges remain in VSC-HVDC grid line protection: (1) Traditional current differential protection has a long delay (1100 ms) problem due to distributed capacitive current. (2) The protection principle based on current correlation is difficult to apply to long transmission lines because the distributed capacitive current is not eliminated. (3) The protection principle based on travelling wave similarity is easily affected by line attenuation, dispersion, and reflection. It has the problems of difficulty in detecting travelling wave signals, a large amount of calculation, and refusal of action at the same time as the main protection. (4) The existing protection principles based on correlation all need to transmit current or travelling wave data to the opposite end, which brings a greater communication burden to the system.

To solve the problems, a new scheme of pilot protection using current integral autocorrelation is proposed in this study. The frequency characteristics of fault current and distributed capacitance current are analysed first, then the current integration is introduced to eliminate distributed capacitance current, and the characteristics of the current integration are analysed in detail. Subsequently, the autocorrelation coefficient is used to describe the difference of current integration between internal and external faults, and a new protection principle based on the autocorrelation coefficient of current integration is proposed. The main contributions of this study are: (1) The method of using integral to eliminate the distributed capacitive current is proposed for the first time in this study, which solves the long delay problem of current differential protection in the time domain. The integral filtering characteristic not only eliminates the effect of distributed capacitor current but also filters out the oscillation of fault current. (2) A protection scheme based on the autocorrelation coefficient is first proposed in this study. The introduction of the autocorrelation coefficient not only reduces the communication burden but also enables the principle of directional protection based on the principle of similarity protection. (3) Compared with the protection principle based on travelling wave similarity, the proposed protection principle has the advantages of low sampling rate, small communication burden, no strict communication synchronisation, simple application, and high reliability. Compared with the protection principle based on current similarity, it eliminates the influence of distributed capacitive current and can be applied to the VSC-HVDC transmission project with long transmission lines. (4) Besides, the proposed protection principle has greater advantages in terms of tolerance to fault resistance (1000 Ω), noise interference (10 dB), communication delay (3 ms), and communication burden, compared with existing protection schemes.

Besides, in Section 2 the fault current oscillation characteristics and the frequency characteristics of distributed capacitor currents are analysed in detail, and the mechanism of current integration filtering distributed capacitance and the current integration characteristics of internal and external faults are analysed. Following that, Section 3 proposes a new principle of fault identification based on the current integral autocorrelation coefficient. The detailed process of the new protection scheme based on the current integral autocorrelation coefficient is described in Section 4. Finally, the validity and superiority of the scheme are verified by simulation of a multi-terminal DC system model. The simulation results are placed in Sections 5 and 6, and conclusions are provided in Section 7.

2 | FAULT CURRENT AND CURRENT INTEGRAL

2.1 | Fault characteristics of VSC-HVDC transmission lines

This study takes the four-terminal VSC-HVDC power grid demonstration project as the research object, and its topology is shown in Figure 1 [17]. This four-terminal simulation model uses the converter of the half-bridge submodule, and its parameters are listed in the Appendix.

When a fault occurs at line1 in Figure 1, the fault current is divided into two stages: The first stage is the discharge of the inverter submodule, and the second stage is the AC system feeding current. The simplified diagram of the fault current at each stage is shown in Figure 13 and is listed in the Appendix. Because the protection scheme studied in this study needs to act
before the converter is blocked, this study only analyses the first stage. In the first stage, all the submodules of the converter will discharge alternately.

Analysis of the equivalent circuit in Figure 13 can obtain the fault current characteristics. The formulas for the transient current in the first stage are [18]:

\[
LC \frac{d^2 u_{dc}}{dt^2} + RC \frac{du_{dc}}{dt} + u_{dc} = 0
\]

(1)

\[
i(t) = AI \sqrt{\frac{C}{L}} e^{-\sigma t} \sin(\omega t + \theta - \beta)
\]

(2)

where \( L \) is the bridge arm reactance, \( R \) is the DC line equivalent resistance, \( C \) is the submodule equivalent capacitance, \( \omega \) is the oscillation frequency, and \( u_{dc} \) is the dc voltage. It can be seen from Equation (2) that the first-stage capacitor discharge is a second-order underdamped oscillation process.

In [16], the characteristics of fault current is analysed in detail, and the influence of distributed capacitive current on traditional current differential protection is verified. Although [16] proposed the protection principle of the DC distribution network, its essence is to ignore the distributed capacitive current instead of eliminating the distributed capacitive current. Therefore, whether it is suitable for VSC-HVDC transmission projects with long transmission lines and large distributed capacitance still needs to be verified.

2.2 Adaptable analysis of protection principle based on the current correlation

The protection scheme based on the current correlation uses the current value as the characteristic value. When the transmission line is short, the protection scheme has better performance, as the distributed capacitance is difficult to affect the overall trend of the current value. If the transmission line is long, the larger distributed capacitance may cause the current oscillation amplitude to be larger. At this time, the fault current on both sides has a weak correlation, which affects the reliability of the protection.

To study the adaptability of the principle of current-dependent protection in long transmission lines, the VSC-HVDC project shown in Figure 1 was used in experiments. The fault time is 1.5–2.0 s, and the sampling frequency is 10 kHz. The simulation result is shown in Figure 2.

As can be seen in Figure 2, due to the large distributed capacitance of long transmission lines, the protection principle based on current correlation requires a delay of 50 ms to accurately determine the fault. Therefore, the distributed capacitance affects the reliability of the protection principle at the beginning of the fault. This is because the protection principle based on the current correlation fails to eliminate the distributed capacitance fundamentally, so it is difficult to apply to the VSC-HVDC project with a long line. The principle of DC transmission line protection based on the correlation of current integration is first proposed in this article. Based on the principle of correlation, current integration is used to eliminate distributed capacitance. This principle can be applied to the VSC-HVDC project with long transmission lines.

2.3 Current frequency characteristics and current integration

The line fault based on the multilevel converter can be divided into two stages. In the capacitor discharge stage, the main component of the internal fault current is the discharge current of the submodule capacitor, and its oscillation frequency can be expressed by Equation (3)[20]:

\[
f = \frac{1}{2\pi} \sqrt{\frac{1}{(2L_0/3+xL_u)6C_0/N} - \left(\frac{xR_u}{2(2L_0/3+xL_u)}\right)^2}
\]

(3)

where \( L_0, C_0, N \) are the bridge arm inductance, submodule capacitance, and bridge arm submodule number, respectively; \( x, L_u, R_u \) is the fault distance, unit inductance, and unit resistance, respectively. In this study, the converter parameters of a VSC-HVDC demonstration project are used to calculate the oscillation frequency, and the obtained result is about 52.6 Hz [20]. The parameters of the VSC-HVDC demonstration: The bridge arm reactance is 15 mH, the submodule capacitance is 600 µF, and the number of single bridge arm submodules is 4.
During external faults, the main component of the fault current is the distributed capacitor current, whose frequency is consistent with the natural frequency of the travelling wave. At this time, the theoretical minimum value of the fault current frequency as follows [20]:

\[ f_i = \frac{\nu}{4d} \]  \hspace{1cm} (4)

where \( \nu \) is travelling wave velocity, and \( d \) is fault distance. It can be seen that the frequency of the distributed capacitor current changes with the fault distance. If the fault distance is 200 km, the current frequency is 375 Hz. It can be seen that the frequency of the internal and external fault currents is different, which is caused by the distributed capacitance of the line. Line distributed capacitance is the main factor affecting the correct operation of traditional current differential protection.

In summary, the oscillation of the fault current and the presence of distributed capacitance will affect the correct operation of the protection. Therefore, this study chooses current integration to achieve the purpose of filtering out the fault current oscillation and eliminating distributed capacitance.

Defining \( i_i, Q \) as the DC fault current and current integral, the relationship between DC fault current and current integral is as follows:

\[ \bar{Q} = \int i_i \, dt \]  \hspace{1cm} (5)

From a mathematical point of view, current integration can be understood as: When the input discrete signal is a unit impulse signal, the output of the integration is a unit step signal. After the Z-transform, it is easy to see that the response is maximum at frequency zero. As the frequency gradually increases, the response decreases, so the process can be seen as a low-pass filtering process. The current integration is the accumulation process of the previous multiple input values. In this process, the jitter between different input values will be passivated, and the jitter with large changes will be passivated, which means that the high-frequency part is suppressed. Hence, distributed capacitor currents exhibit high-frequency characteristics, so the use of current integration to handle fault currents can minimise the effects of distributed capacitor currents and eliminate the oscillation of fault current.

### 2.4 Fault current integration characteristics

Integral is an important concept in mathematical analysis. Current integral represents the vector value of the area surrounded by the integrand and the coordinate axis. In order to analyse the changing trend of the fault current integral with the fault current, a simulation model was set to generate a line short-circuit fault, and the fault current waveform was obtained as shown in Figure 3. The fault current waveform in Figure 3 is oscillating, which validates the previous analysis.

The two curves in Figure 3 are the fault current waveforms, so the current integration is the vector value of the area enclosed by the three lines of the fault current curve, \( y = 0 \) and \( x = 0 \).

![Figure 3. Current waveform on both sides of internal fault](image)

### Table 1 Fault current integration characteristics

| Condition   | Positive pole | Negative pole |
|-------------|---------------|---------------|
| Normal      | +             | –             |
| Internal fault | +           | +             |
| External fault | +           | –             |

The analysis of current integration by fault current is as follows: (1) In the normal state, the M terminal current is positive and the N terminal current is negative; so the M terminal current integral is positive and continues to increase, and the N terminal current integral is negative and continues to decrease. (2) When an internal fault occurs, the M terminal current increases, so the M terminal current integral is still positive and keeps increasing, while the N terminal current reverses to zero, and its current integration of the line starts to increase. (3) When an external fault occurs, the direction of the M terminal current is still positive and continues to increase, so its current integral increases. At this time, the direction of the N terminal current does not reverse, so its current integral keeps decreasing. The above analysis is the fault current integral characteristic of the positive line, and the fault current integral characteristic of the negative line is just the opposite.

In summary, there is a significant difference in the current integration between internal and external faults. The fault current integral characteristics are summarised in Table 1 (+' representative of increase, ‘–’ representative of decrease).

In order to express the current integral change trend, this study proposes to use the autocorrelation coefficient as a tool to measure the current integral change trend.

### 3.1 Autocorrelation

According to the analysis in the previous section, internal and external faults can be distinguished by current integral trends.
In this study, the autocorrelation coefficient commonly used in data mining is used to describe the fault current integral change trend [21]. The autocorrelation function is a tool to measure the degree of correlation of the same event at different times. Defining the signal as \( x(n) \), its autocorrelation function is as follows:

\[
    r_x(m) = \sum_{n=-\infty}^{\infty} x(n)x(n + m)
\]

(6)

The autocorrelation function reflects the similarity of the signals in the two time periods. In actual engineering, the autocorrelation coefficient is often used to replace the autocorrelation function. Dividing Equation (6) by the square root of the respective energy product and normalising it can get Equation (7).

\[
    r = \frac{\sum_{n=0}^{\infty} x(n)x(n + m)}{\sqrt{\sum_{n=0}^{\infty} x^2(n) \sum_{n=0}^{\infty} x^2(n + m)}}
\]

(7)

where \( r \) is the autocorrelation coefficient of \( x(n) \), if \( x(n) \) is replaced by \( \bar{x} \), \( r \) is the autocorrelation coefficient of current integral. According to Schwartz’s inequality, it can be concluded as follows:

\[
    |r| \leq 1
\]

(8)

### 3.2 Protection principle of correlation

A detailed description of the current integral autocorrelation coefficient as a protection criterion is as follows: At the moment of a line fault, the autocorrelation coefficients are calculated for the current integration at both sides of the line. If the autocorrelation coefficient is positive, it means that the current integration at the time of the fault has the same trend as the normal state. If the autocorrelation coefficient is negative, it means the changing trend is the opposite. It can be known from Table 1 that if the M terminal autocorrelation coefficient is positive and the N terminal autocorrelation coefficient is negative, the fault type is judged as an internal fault. If the M and N terminals autocorrelation coefficients are both positive, the fault type is judged as an external fault.

The above analysis ignores factors such as noise, communication delay, and current transformer errors. In actual engineering, the current transformer has a certain error due to its remanence, environmental influences, and other factors. The maximum error of the current transformer during normal operation is 10% [19]. In addition, the communication delay and noise interference of overhead transmission lines cannot be ignored. In summary, this study sets the threshold of the autocorrelation coefficient to 0.9 and –0.9 to reduce the impact of various factors.

The fault identification criteria are summarised as follows:

\[
    \begin{cases} 
    \text{M terminal} : r_M > 0.9 & \text{Internal fault} \\
    \text{N terminal} : r_N < -0.9 & \text{Internal fault} \\
    \text{M terminal} : r_M > 0.9 & \text{External fault} \\
    \text{N terminal} : r_N < -0.9 & \text{External fault} 
    \end{cases}
\]

(9)

where \( r_M \) and \( r_N \) is the autocorrelation coefficient of the current integration on both sides of the line. Essentially, the protection principle of the autocorrelation coefficient uses all transient information of the current for fault identification, and it is more reliable than the protection principle uses single fault information. This principle has the ability to eliminate waveform oscillation and anti-noise interference because it uses the characteristics of integration. In addition, this principle only needs to transmit logic signals, which reduces the effect of communication synchronisation errors.

### 4 PROTECTION SCHEME PROCESS

#### 4.1 Startup element based on current differential

The starting element of the proposed protection principle is assumed by \( \frac{di}{dt} \). Under normal operating conditions, the amount of current mutation is very small (not considering power transfer). When the DC system fails, the current derivative must change with current fluctuations. Considering the presence of harmonics during operation, the threshold is set to a value slightly greater than zero. Therefore, the formula of the starting element in this study is as follows:

\[
    \left| \frac{di}{dt} \right| > k_{set}
\]

(10)

where \( k_{set} \) is the threshold set by considering factors such as harmonics.

#### 4.2 Fault pole selection based on area ration

Fault pole selection is an indispensable part of DC protection. The area method is proposed as the criterion for fault pole selection in this study. When a pole-to-ground fault occurs, the change of the fault pole is much larger than the healthy pole, which means that the area of the fault pole is larger than the area of the healthy pole; however, the area of the pole-pole line is the same when the pole-pole fault occurs. So the description of the fault selection criterion using the area method is as follows:

\[
    \begin{cases} 
    \text{positive pole - ground fault} : \left| \bar{I}_{p} \right| / \left| \bar{I}_{g} \right| > k_{set1} \\
    \text{negative pole - ground fault} : \left| \bar{I}_{g} \right| / \left| \bar{I}_{p} \right| < k_{set2} \\
    \text{pole - pole fault} : k_{set2} < \left| \bar{I}_{g} \right| / \left| \bar{I}_{p} \right| < k_{set1} 
    \end{cases}
\]

(11)
According to the analyses in Sections 3 and 4, the steps of the protection scheme are described in detail as follows. In addition, the program flowchart is described in Figure 4.

**Step 1:** First, the protection device performs a data acquisition program and calculates the current. Then, the current is substituted into the starting element. If the fault start criterion is met, the process enters the next step, otherwise the process returns.

**Step 2:** If the previous step is satisfied, the current integration value is calculated for the fault identification and the fault pole selection programs. In order to reduce the protection time, the fault identification and the fault pole selection programs are run simultaneously.

**Step 3:** In the second step, if the result of the fault detection is the external fault, the program returns. If Equations (9) and (11) both meet the conditions, the protection device selects fault pole and sends an action signal. After the protective action signal is issued, the program ends.

In this study, the current is continuously sampled (10 kHz) by a protection device. After the startup element action, the current of 1 ms before and after the fault is used to calculate the current integral. This study uses the recursive algorithm to obtain nine current integral values before and after each fault. Then, three sampling points are selected after the fault and three sampling points before the fault to calculate the autocorrelation coefficient, and seven autocorrelation coefficients can be obtained. Therefore, this protection scheme calculates the autocorrelation coefficient seven times within 2 ms.

### 4.4 Analysis of action time

It can be seen from the previous section that the proposed protection principle uses 1 ms data before and after the fault to calculate the current integral and autocorrelation coefficient. Therefore, the protection criterion can be obtained within 1 ms ($t_1$) after the fault.

Also, the computational time of the algorithm needs to be considered, as it involves some statistical analysis. Microcomputer protection devices often use digital signal processing (DSP) to process data. Take TMS320F2812 as an example. Its cycle is 6.67 ns due to the system clock being 150 MHz. According to Equations (5) and (7), the clock period of the algorithm in this study is 82. Therefore, the calculation time of the algorithm in this study is $t_c = 0.5469 \mu s$. The conversion time of TMS320F2812 is determined by the input clock and sampling period and does not exceed 1 $\mu s$. Considering other configuration time, set the calculation time of this algorithm is $t_c = 0.5469 \mu s$ [20].

Moreover, other time factors such as photoelectric conversion and measurement delays are considered. Because the above factors are on the microsecond level, so $t_3 = 0.1 \text{ ms}$ is set as the sum of other factors. Finally, the communication delay is an indispensable part of calculating the differential protection time as many factors cause communication delay. Transmission media, digital equipment, converters, and so forth will all produce communication delay. Therefore, the calculation formula of communication delay ($t_d$) is as follows:

$$t_d = t_r + t_p + t_c \times n + t_0$$

where $t_c$ is the transmission delay of the equipment, which is related to the equipment and transmission speed grade, and its time does not exceed 0.1 ms; $t_0$ is the delay of terminal equipment, including Pulse Code Modulation (PCM) multiplexer and connecting circuit. The delay generated by the PCM terminal is about 600 $\mu s$. The delay setting is $t_d = 1 \text{ ms}$ considering other factors; $t_p$ is the delay of the multiplexer, and its value is 0.1 ms; $n$ is the number of light intervals; $t_c$ is the transmission delay of the signal, and its value is 4.9 $\mu s$/km. Since the longest line in the model in Figure 1 does not exceed 250 km, $t_0 = 1.225$ ms. Therefore, the communication delay can be calculated as $t_d < 0.1 + 0.5 + 1.225 = 2.825$ ms. In fact, the standard for communication delay in China is no more than 5 ms.

In summary, the operating time ($T$) that can be protected is as follows: $T = t_1 + t_2 + t_3 + t_d \approx 4.425$ ms. Compared with
the action time of the existing backup protection (1100 ms), the protection principle proposed in this study has great advantages.

5 | SIMULATION

The proposed protection is verified by simulation in this section. The simulation model used in this section comes from Section 1, and the detailed parameters of the four-terminal simulation model are shown in the Appendix. The parameters of this simulation are set as follows: (1) The fault location is set at \( f_1 \) and \( f_2 \) of the line, the fault types are pole-to-ground fault and pole-pole fault. (2) The fault time is 1.5–2.0 s, and the sampling frequency is 10 kHz.

5.1 | Internal pole-pole fault

An internal pole-pole short-circuit fault is set at the \( f_1 \) in the line1 at 1.5 s. The fault distance is 100 km and transition resistance is 0 Ω. In order to show the changing trend of fault current oscillation and current integral, this study selects the fault waveform of 1.45–1.6 s, and the fault time is 1.5 s. The simulation results are shown in Figure 5.

Figures 5(a) and (b) show the fault currents of positive and negative poles, respectively. It can be seen from Figures 5(a) and (b) that the fault current has the characteristics of oscillation in the early stage of the fault. According to the analysis in Section 2, the distributed capacitor current is the main cause of fault current oscillation in the figure. Figures 5(c) and (d) show the fault currents integral of positive and negative poles, respectively. Comparing Figures 5(a) and (b) with (c) and (d), it can be clearly seen that current integration has the effect of eliminating current oscillations.

In addition, Figures 5(c) and (d) demonstrate that when an internal fault occurs, the positive current integral increases, and the negative current integral decreases. Therefore, the simulation results of current integration are exactly the same as the theoretical analysis in the first section. As a result, the simulation results in Figure 5 verify the correctness of the theoretical analysis in Section 2.

5.2 | Internal positive pole-to-ground fault

An internal positive pole-to-ground fault is set at the \( f_1 \) on the line1. The fault distance is 100 km and transition resistance is 0. The measured currents and current integrated values on both sides of the line are shown in Figure 7. Similarly, the current differential, autocorrelation coefficient, and current area ratio
Figure 7 Simulation results of internal positive pole-to-ground fault (a) positive fault current, and (b) positive fault current integral

Figure 8 Protect simulation results of internal positive pole-pole fault (a) positive current differential (starting element), (b) positive autocorrelation coefficient (fault identification), and (c) current integral ratio (fault pole selection)

during internal pole-to-ground fault are calculated as shown in Figure 8.

If the bipolar system adopts a large-resistance grounding method, the pole-to-ground fault current is very small, and it is considered that no fault has occurred. Therefore, the simulation system in this study adopts the method of midpoint metallic grounding. Detailed analysis in this section is the same as the internal pole-pole fault. By comparing Figures 5 with 7 and 8 with 6, the conclusion is as follows: The starting element and the fault identification element in Figures 8(a) and (b) can judge that an internal fault has occurred at this time. The fault pole selection element in Figure 8(c) is greater than 5, so a positive pole-to-ground fault occurs at this time. The reason for the above result is that the pole-pole fault and the pole-to-ground fault have the same fault characteristics.

In summary, the protection scheme proposed in this study can operate correctly when an internal pole-to-ground line fault occurs.

5.3 External fault

An external pole-pole fault occurs at point $f_2$ at 1.5 s. The fault distance is 10 km to Modular Multilevel Converter (MMC2) and transition resistance is 0. The measured currents and current integrated values on both sides of the line are shown in Figure 9.

Figures 9(a) and (b) show that the fault current still oscillates when an external fault occurs. The current integration in Figures 9(c) and (d) shows that integration can eliminate current oscillations. Besides, the current integration in Figures 9(c) and (d) indicates that when an external fault occurs, the current integration transformation trend of the M terminal and the N terminal does not change. The simulation results of fault current and fault current integration are consistent with the analysis in Section 2.

To verify the correctness of the protection, the starting element, fault identification element, fault pole selection element are calculated as shown in Figure 10.

The meaning of each figure in Figure 10 is the same as Figure 6, the following conclusions can be drawn in Figure 10:
(1) The current differential in Figure 10(a) can increase rapidly when a fault occurs in 1.5 s, indicating that the starting element can act quickly and reliably. (2) Before the fault occurs, the autocorrelation coefficients in Figure 10(b) are all greater than 0.9. This is because the current integral changes at both ends of the line are the same. When a fault occurs (1.5 s), the autocorrelation coefficient of M and N terminals does not change due to the unchanged trend of the current integration. Therefore, it is determined that an external fault has occurred. (3) Figure 10(c) shows that the current integral ratio of positive and negative is between 0.6 and 1.5. According to formula (11), it can be judged that an external pole-pole fault occurs at this time.

In summary, since the fault identification element determines that it is an external fault at this time, so the protection will not operate. Simulation results can prove the correctness of the protection principle.

6 PROTECTION PERFORMANCE ANALYSIS

6.1 Influence of DC line-distributed capacitance

The current integration can eliminate waveform oscillations and suppress high-frequency signals. Also, this protection scheme only compares the correlation of the current integral, which reduces the influence of waveform oscillation. Therefore, the protection scheme is not affected by distributed capacitors in theory.

To analyse the influence of the distributed capacitance in the DC line, a distributed capacitive parameter of eight times the original value is set (the original line parameters are listed in Table A3 in the Appendix).

Waveforms of currents measured at both terminals are illustrated in Figure 11(a). Because of the influence of distributed capacitance current during a fault, there is a transition process (red ring) at the beginning of the fault as shown in Figure 11(a). The current on both sides oscillates, and if oscillation becomes increasingly obvious, the amplitude fluctuation will be serious. Therefore, such irregular fluctuations will bring the risk of misoperation to traditional differential protection. When applying the protection scheme presented in this study, the waveforms of current integration measured at both terminals are illustrated in Figure 11(b). It can be seen that the current integration can filter out the current fluctuations and suppress the high-frequency signal (distributed capacitor current signal). Therefore, the autocorrelation coefficient can be calculated and plotted in Figure 11(c). It can be seen from Figure 11(c) that the protection can operate correctly.

Table 2 compares the ability of the proposed protection principle with other protection principles to withstand fault resistance.

| Distributed capacitance | Twice | Four times | Eight times | Tenfold |
|-------------------------|-------|------------|-------------|---------|
| Current differential protection | ✓ | ✓ | ✓ | ✓ |
| Protection principle [16] | ✓ | ✓ | ✓ | ✓ |
| Proposed protection | ✓ | ✓ | ✓ | ✓ |
| Protection principle [15] | ✓ | ✓ | ✓ | ✓ |

The results show that the proposed protection principle and [15] can withstand a fault resistance of 1000 Ω, while [16] can only withstand a fault resistance of 400 Ω. Therefore, the proposed protection principle has a strong ability to withstand fault resistance. Although high-resistance grounding will reduce the amplitude of the fault current, the proposed protection

6.2 Influence of fault resistance and noise

Fault resistance is an important factor in evaluating protection performance. Different faults with different fault resistance on Line 1 (f) are simulated in this study to test the proposed protection scheme. Table 3 shows that the fault resistance cannot affect the correct operation of the protection scheme proposed in this study. Actually, the performance of the proposed protection action is determined by the correlation of the current integration autocorrelation and does not rely directly on the magnitude of the fault current. So the protection can work correctly in different fault resistance.

Table 4 compares the ability of the proposed protection principle with other protection principles to withstand fault resistance.

The results show that the proposed protection principle and [15] can withstand a fault resistance of 1000 Ω, while [16] can only withstand a fault resistance of 400 Ω. Therefore, the proposed protection principle has a strong ability to withstand fault resistance. Although high-resistance grounding will reduce the amplitude of the fault current, the proposed protection
TABLE 3 Test of the capability to withstand fault resistance

| Fault location         | Fault resistance (Ω) | r (M terminal) | r (N terminal) | Action |
|------------------------|----------------------|---------------|---------------|--------|
| Pole-to-pole           | 200                  | 0.998         | −0.982        | √      |
|                        | 500                  | 0.972         | −0.991        | √      |
|                        | 1000                 | 0.995         | −0.987        | √      |
| Positive pole-to-ground| 200                  | 0.984         | −0.998        | √      |
|                        | 500                  | 0.979         | −0.982        | √      |
|                        | 1000                 | 0.989         | −0.985        | √      |
| Negative pole-to-ground| 200                  | 0.992         | −0.991        | √      |
|                        | 500                  | 0.989         | −0.986        | √      |
|                        | 1000                 | 0.991         | −0.975        | √      |

TABLE 4 Comparison of the capability to withstand fault resistance

| Fault resistance/Ω | 200 | 400 | 600 | 1000 |
|--------------------|-----|-----|-----|------|
| Protection principle [16] | √   | √   | ×   | ×    |
| Proposed protection | √   | √   | √   | √    |
| Protection principle [15] | √   | √   | √   | √    |

TABLE 5 Comparison of the capability to noise in internal fault

| Noise     | 40 dB | 30 dB | 20 dB | 10 dB |
|-----------|-------|-------|-------|-------|
| Current differential protection | √     | √     | ×     | ×     |
| Protection principle [16] | √     | √     | √     | ×     |
| Proposed protection | √     | √     | ×     | √     |
| Protection principle [15] | √     | √     | ×     | ×     |

Comparing Figures 12 and 6, it can be concluded as follows: 10 dB noise ratio is difficult to affect the correct action of the proposed protection principle. The proposed protection principle has a strong ability to withstand noise interference.

To prove the superiority of the proposed protection principle in anti-noise interference, white noise with different noise ratios is added to the traditional protection principle and the proposed protection principle, respectively. The simulation results are listed in Table 5. As shown in Table 5, the current differential protection does not misoperate to the fault under 30 dB noise, while protection principle based on current correlation [16] does not misoperate to the fault under 20 dB noise. Notably, only the proposed protection operated correctly under 10 dB noise.

6.3 Influence of communication delay

Communication delay is a problem that cannot be ignored for VSC-HVDC protection. VSC-HVDC power grids often use optical fiber communication and its speed is 200 km/ms [19]. Since the line length of the simulation system in this study does not exceed 250 km, the communication delay is less than 1.25 ms. In addition, the time window of the proposed protection principle is 1 ms, and taking into account the time of data conversion, hardware export, and so forth, the protection can operate within 6 ms. Therefore, the operation time of the proposed protection principle can meet the requirements of VSC-HVDC transmission line backup protection.

Figure 13 shows the autocorrelation coefficients on both sides of the line during internal faults. Since the communication
Figure 13: Autocorrelation coefficient of internal fault

Table 6: Internal fault test result of protections under communication delay

| Communication delay | r (M terminal) | r (N terminal) | Correct action |
|---------------------|---------------|---------------|---------------|
| 0.5 ms              | 0.9873        | -0.9831       | √             |
| 1 ms                | 0.9801        | -0.9870       | √             |
| 1.5 ms              | 0.9759        | -0.9711       | √             |
| 2 ms                | 0.9792        | -0.9854       | √             |
| 2.5 ms              | 0.9810        | -0.9799       | √             |
| 3 ms                | 0.9715        | -0.9741       | √             |

The delay of the Chinese standard is not more than 5 ms, Figure 13 only shows the fault data with 5 ms (1.5~1.505 ms). It can be seen from Figure 13 that the autocorrelation coefficients on both sides of the line remain unchanged after the fault. This is because the changing trend of the fault current integral does not change with the fluctuation of the fault current. Even if there is a very large communication delay, the proposed protection principle can guarantee the correctness. Therefore, the communication delay can hardly affect the correct operation of the proposed protection principle.

In order to prove the performance of the proposed protection principle under large communication delay, 0.5~3 ms communication delay is added to the simulation data. The simulation results are listed in Table 6.

Table 7 compares the requirements for communication synchronisation between the proposed protection principle and other protection principles. The simulation results show that [15, 16] can only withstand a delay of 0.3 ms, and only the proposed protection principle can withstand a delay of 1.5 ms. Since the changing trend of the fault current integral remains unchanged, the autocorrelation coefficient remains unchanged, and the proposed protection principle only compares the autocorrelation coefficients at both ends, so the proposed protection principle can operate correctly with a communication delay of 3 ms.

### 6.4 Comparison and discussion

In the previous work, several backup protections of VSC-HVDC transmission lines are proposed. In [15], a protection principle based on the similarity of travelling waves is proposed. In [16], a protection principle based on current similarity is proposed. Next, the three protection principles will be compared in detail in this article. The comparison results are listed in Table A1 in the Appendix. The detailed explanation of Table A1 is as follows:

1. Based on the analysis of the frequency characteristics of the distributed capacitor current, this study uses the integral characteristic to eliminate the distributed capacitor current, so the proposed protection principle completely solves the problem of the distributed capacitor current. In [15], the travelling wave similarity construction criterion is used, so it is not affected by distributed capacitance current in principle. However, [16] only uses the current similarity to construct the protection criterion, and its essence is to use the characteristic so that the similarity is not easily affected by small fluctuations. The essence of its protection principle is to ignore the distributed capacitive current instead of eliminating it. Therefore, the protection principle of [16] can be applied to short distribution lines, but it is not suitable for long transmission lines.

2. Besides, the communication burden is an issue that has to be considered in the design of protection principles. The protection principle in [15] needs to transmit a travelling wave signal to the opposite end, and [16] needs to transmit a current signal to the opposite end. Therefore, both protection principles bring a greater communication burden to the system. However, the protection principle proposed in this study completes the calculation of the autocorrelation coefficient locally and only needs to transmit logic signals from the opposite end. Therefore, the protection principle proposed in this study is much smaller in the communication burden and demand for data synchronisation, compared to [15, 16].

3. The characteristic value of the protection principle in [15] is a travelling wave signal, but the travelling wave signal is extremely susceptible to line attenuation, dispersion, and reflection. Moreover, the travelling wave signal has the problem of difficult detection and short existence time. The above difficulties seriously affect the reliability of [15]. In fact, since the main protection of the DC project adopts travelling wave protection, the backup protection principle based on the phase relationship of the travelling wave will have the...
possibility of failure at the same time as the travelling wave protection.

4. Since [15] uses the travelling wave signal as the characteristic value, it may fail simultaneously with the travelling wave's main protection. Therefore, the reliability of the protection principle of [15] is lower than that of the proposed protection principle. Moreover, the proposed protection principle can withstand 10 dB noise interference, while the protection principles in [15, 16] can only withstand 20 dB noise interference at most. Compared with the other two protection principles, the proposed protection principle can operate correctly with a communication delay of 3 ms.

7 | CONCLUSION

In this study, a novel protection scheme based on the autocorrelation coefficient of transient current integration is proposed to meet both the speed and selectivity requirement of DC line protection in the VSC-HVDC system. The proposed protection principle uses the autocorrelation coefficient of current integral to identify faults. The advantages of the proposed protection principle are shown as follows:

1. The use of integral characteristics not only eliminates the effect of distributed capacitor currents but also filters out fault current oscillations.
2. The use of the autocorrelation coefficient reduces the burden of hardware communication. The proposed protection principle has small requirements for communication synchronisation.
3. Simulation results prove that the proposed protection principle can rapidly and accurately operate and tolerate the uncertainty caused by up to 1000 Ω fault resistance, 10 dB noise and 3 ms communication delay. Therefore, the proposed protection principle has advantages over the previous backup protection scheme in terms of withstanding the effects of transition resistance, noise interference and distributed capacitor current, and is more economical.

Therefore, the proposed protection principle provides a new idea for the backup protection of the VSC-HVDC transmission system and has a good engineering application prospect.

ACKNOWLEDGEMENTS

This work was supported by the National Key R&D Program of China under grant no. 2018YFB0904600, the State Grid Corporation technology project (no. 5200–201956113A-0-0-00).

REFERENCES

1. Monadi, M., et al.: Multi-terminal medium voltage DC grids fault location and isolation. IET Gener. Transm. Distrib. 10(14), 3517–3528 (2016)
2. Yanfei, C., et al.: Coordination strategies for securing AC/DC flexible transmission networks with renewables. IEEE Trans. Power Syst. 33(6), 6309–6320 (2018)
3. Jinghan, H., et al.: Review of protection and fault handling for a flexible DC grid. Prot. Control Mod. Power Syst. 5(2), 151–165 (2020)
4. Meng, L., et al.: Six harmonic-based fault location for VSC-DC distribution systems. IET Gener. Transm. Distrib. 11(14), 3485–3490 (2017)
5. Wang, X., et al.: A transient voltage-based DC fault line protection scheme for MMC-based DC grid embedding DC breakers. IEEE Trans. Power Delivery 34(1), 334–345 (2019)
6. Xing, H., Li, Q., Jiuping, P.: A new protection scheme for MMC-based MVDC distribution systems with complete converter fault current handling capability. IEEE Trans. Ind. Appl. 55(5), 4515–4523 (2019)
7. Jeremy, S., Athula, D.R.: Fault detection and interruption in an earthed HVDC grid using ROCOV and hybrid DC breakers. IEEE Trans. Power Delivery 31(3), 973–981 (2016)
8. Dekert, K., et al.: Wavelet-based protection strategy for DC faults in multi-terminal VSC-HVDC systems. IET Gener. Transm. Distrib. 5(4), 496–503 (2011)
9. Zheng, Z., et al.: A transient harmonic current protection scheme for HVDC transmission line. IEEE Trans. Power Delivery 27(4), 2278–2285 (2012)
10. Guobing, S., et al.: A new whole-line quick-action protection principle for HVDC transmission lines using one-end current. IEEE Trans. Power Delivery 30(2), 599–607 (2015)
11. Xiaolei, L., Osman, A.H., Malik, O.P.: Hybrid traveling wave/boundary protection for monopolar HVDC line. IEEE Trans. Power Delivery. 24(2), 1750–1750 (2009)
12. Xiaolei, L., Osman, A.H., Malik, O.P.: Real-time implementation of a hybrid protection scheme for bipolar HVDC line using FPGA. IEEE Trans. Power Delivery 26(1), 101–108 (2011)
13. Sandeep, B., Monalisa, B., Malik, O.P.: Hilbert Huang transform based online differential relay algorithm for a shunt-compensated transmission line. IEEE Trans. Power Delivery 35(6), 2803–2811 (2018)
14. Min, X., et al.: A sensitive and high-speed traveling wave protection scheme for HVDC transmission line. Int. Trans. Electr. Energy Syst. 25(6), 393–404 (2015)
15. Yanting, W., et al.: A pilot protection scheme for transmission lines in VSC-HVDC grid based on similarity measure of traveling waves. IEEE Access 7, 7147–7158 (2019)
16. Ke, J., Congbo, W., Tianshu, B., et al.: Transient current correlation based protection for DC distribution system. IEEE Trans. Ind. Electron. 67(11), 9301–9311 (2020)
17. Bin, L., et al.: A novel single-ended transient-voltage-based protection strategy for flexible DC grid. IEEE Trans. Power Delivery 34(5), 1925–1937 (2019)
18. Jin, Y., John, E.F., John, O.: Short-circuit and ground fault analyses and location in VSC-based DC network cables. IEEE Trans. Ind. Electron. 59(10), 3827–3837 (2012)
19. Ke, J., et al.: Transient current waveform similarity based protection for flexible DC distribution system. IEEE Trans. Ind. Electron. 66(12), 9301–9311 (2019)
20. Meng, L.: Study on protection of VSC-DC distribution system. Dissertation, North China Electric Power University (2018)
21. Sanborn, S., Ma, X.: Quantifying information content in data compression using the autocorrelation function. IEEE Signal Process. Lett. 12(3), 230–233 (2005)
22. Kuntal, S., et al.: Short-time Fourier transform based transient analysis of VSC interfaced point-to-point DC system. IEEE Trans. Ind. Electron. 65(5), 4080–4091 (2018)

How to cite this article: Wu C, Zhang D, Luo G, Li M, He J. A novel protection scheme for VSC-HVDC transmission lines based on current integral autocorrelation. IET Gener Transm Distrib. 2021;15:1858–1870. https://doi.org/10.1049/gtd2.12140
APPENDIX
See Table A1 to A3 and Figure A1.

TABLE A1  Comparison of three protection principles

| Proposed protection | [15] | [16] |
|----------------------|------|------|
| Line range           | Long line | Long line | Short line |
| Eliminate distributed capacitive current | Yes | Yes | No |
| Communication burden | Small | large | large |
| Calculation amount   | Medium | large | Small |
| Demand for data synchronism | Very small | small | small |
| Affected by line attenuation, dispersion and refraction | No | Yes | No |
| Difficult in collecting data | No | Yes | No |
| Reliability          | High | Lower | High |
| Noise tolerance      | 10 dB | 30 dB | 20 dB |
| Affected by distributed capacitive current | No | No | Yes |
| Fault resistance     | 1000 Ω | 1000 Ω | 400 Ω |
| Communication delay  | 3 ms | 0.3 ms | 0.3 ms |

TABLE A2  Main parameters of four-terminal MMC-HVDC

| Parameters                                    | MMC1, MMC2 | MMC3, MMC4 |
|-----------------------------------------------|------------|------------|
| Number of single bridge arm submodules       | 244        | 244        |
| Submodule capacitance (mF)                    | 8          | 8          |
| Submodule voltage (kV)                        | 2.193      | 2.193      |
| IGBT parameters                               | 4.5 kV/2kA | 4.5 kV/3kA |
| Bridge arm reactor (mH)                       | 100        | 75         |
| Rated capacity (MVA)                          | 850        | 1700       |
| Short-circuit impedance (p.u.)                | 0.15       | 0.18       |
| AC rated voltage (kV)                         | 230/525    | 230/525    |
| Converter valve-side rated voltage (kV)      | 290.88     |            |
| Current-limiting inductance (mH)              | 150        |            |

TABLE A3  Line parameters of four-terminal MMC-HVDC

| Line parameters | Resistance (Ω/km) | Inductance (mH/km) | Capacitance to the ground (µF/km) |
|-----------------|-------------------|--------------------|-----------------------------------|
| Line1, line2    | 0.00995           | 0.86               | 7.90 \times 10^{-3}              |

FIGURE A1  Equivalent circuit diagram (a) discharging stage, (b) stage after blocking