A Novel Protection Scheme for MMC-HVDC Transmission Lines Based on Cross-Entropy of Charge

CHUANJIAN WU, (Graduate Student Member, IEEE), DAHAI ZHANG, (Member, IEEE), AND JINGHAN HE, (Fellow, IEEE)
School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China
Corresponding author: Dahai Zhang (dhzhang1@bjtu.edu.cn)
This work was supported by the National Key Research and Development Program of China under Grant 2016YFB0900600.

ABSTRACT MMC-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. Besides, the existing backup protection scheme has the problems of long delay and strict communication synchronization requirements. Therefore, this paper proposes a novel protection scheme for mmc-HVdc transmission lines based on the Cross-Entropy of charge. The fault current oscillation phenomenon and fault current frequency characteristics of mmc-HVdc transmission lines are analyzed first. Secondly, this paper proposes a method to filter out distributed capacitance current by charge and eliminate the current oscillation. Finally, the difference of the charge during different faults (internal fault and external fault) is analyzed, and the Cross-Entropy is introduced to express this difference. Hence, this paper proposes a new principle of identifying faults using the Cross-Entropy of the charge. Simulation results show that the protection principle is not affected by the distributed capacitive current and does not require strict communication synchronization. It has excellent performance in intolerance to fault resistance and noise interference and can be used as backup protection for the mmc-HVdc transmission system.

INDEX TERMS MMC-HVdc systems, backup protection, charge, cross-entropy.

I. INTRODUCTION
MMC-HVdc has great advantages in solving new energy grid connections, central load power supply, and regional grid interconnection. Building a mmc-HVdc grid based on existing mmc-HVdc projects has also become a future trend [1]–[4]. However, when the mmc-HVdc transmission line fault, 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 [5]–[7]. 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 signals or double-ended signals. Traveling 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 [8]. References [9], [10] studied current differential protection and voltage differential protection, respectively. Those papers use the wavelet transform coefficient and differential of current or voltage to constitute fault criteria. References [11], [12] use the high-frequency signal attenuation characteristics of line boundary elements to construct single-ended protection principles. The fault detection scheme based on wavelet transform in reference [13] has some problems, such as high sampling frequency and difficult information extraction. Reference [14] proposes an
overcurrent protection on Voltage-Source-Converter-Based. Difficulty in identifying long-distance high-impedance faults is a common problem in the above-mentioned single-ended protection.

The protection scheme which is based on a double-ended signal is mostly differential protection, it has absolute selectivity and is little affected by high transition resistance. But it is easily affected by the distributed capacitance current of the line. Reference [15] proposed a protection scheme based on traveling wave direction. However, it has the disadvantages that traveling wave signals are difficult to extract and are greatly affected by high-frequency signals. To solve the problem that current differential protection is affected by the distributed capacitance of the line, differential protection that compensates the distributed capacitance current was proposed in [16], [17]. However, the scheme for compensating distributed capacitance is complicated, and there are difficulties in application. Since traveling waves are not affected by distributed capacitance, reference [18] proposes a traveling wave differential protection. However, the short time of the traveling wave signal leads to a decrease in the reliability of the protection.

Since the traditional protection scheme still has some shortcomings, some scholars introduce the concept of correlation and expect to study a new type of protection principle. Reference [19] proposed a protection principle based on the traveling wave correlation coefficient. However, it has the disadvantages of a large amount of calculation, heavy communication burden, difficult detection, and low reliability. Reference [20] proposed a protection principle based on the transient current correlation coefficient. Since the protection principle based on the transient current cannot eliminate the distributed capacitive current, a longer line may cause a long delay in the protection principle based on the transient current.

So, the following challenges remain in mmc-HVdc line protection: 1) Traditional current differential protection has a long delay (1100ms) 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 the frequency domain relies on extracting the information on a single frequency to solve the distributed capacitance current, but at the same time, it brings the problem of low reliability. 4) The protection principle based on traveling wave similarity is easily affected by line attenuation, dispersion, and reflection. It has the problems of difficulty in detecting traveling wave signals, a large amount of calculation.

To solve those problems, a new protection scheme using cross-entropy of charge is proposed in this paper. The frequency characteristics of fault current and distributed capacitance current are analyzed first. Then, the charge is introduced to eliminate distributed capacitance current and the characteristics of the charge are analyzed in detail. Subsequently, the cross-entropy is used to describe the difference of charge between internal and external fault, and a new protection principle based on the cross-entropy of charge is proposed. The main contributions of this paper are as follows: 1) The method of using charge to eliminate the distributed capacitive current is proposed for the first time in this paper, which solves the long delay problem of current differential protection in the time domain. The charge 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 cross-entropy is first proposed in this paper. The introduction of the cross-entropy reduces the communication burden of the protection device. 3) Compared with the protection principle based on traveling wave similarity, the proposed protection principle has the advantages of low sampling rate, no strict communication synchronization, simple application, and high reliability. Compared with the protection principle based on current similarity, it eliminates the influence of distributed capacitor current and can be applied to long transmission lines. 4) Besides, the proposed protection principle has greater advantages in terms of tolerance to fault resistance (1000Ω), noise interference (10dB), communication delay (1.5ms), and communication burden compared with existing protection schemes.

Besides, the oscillation characteristics of the fault current and the frequency characteristics of the distributed capacitance current are analyzed in detail in Section II. In Section III, the theoretical derivation of charge filtering distributed capacitance current is introduced first. Subsequently, the difference of charge between internal faults and external faults is analyzed, and a method of expressing this difference using cross-entropy is proposed. The detailed process of the new protection scheme based on the cross-entropy of charge is described in Section IV. Finally, the validity and superiority of the scheme are verified by simulation. The simulation results are placed in Section V and conclusions are provided in Section VI.

II. ANALYSIS OF FAULT CHARACTERISTICS

A. FAULT CHARACTERISTICS OF MMC-HVDC TRANSMISSION LINES

This paper takes the mmc-HVdc demonstration project as the research object, and its topology is shown in Fig. 1 [21].

![Figure 1. MMC-HVdc grid test system.](image)

This two-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, the fault current is divided into two stages: the first stage is the discharge of the inverter sub-module, and the second stage is the ac system feeding current. The simplified diagram of the fault current
at each stage is shown in the Appendix. In the first stage, all the sub-modules of the converter will discharge alternately.

Analysis of the equivalent circuit can obtain the fault current characteristics. The formulas for the transient current ($i_t$) [22], [23] in the first stage are shown as:

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

\[
i_t = A \sqrt{\frac{C}{L}} e^{-\alpha t} \sin(\omega t + \theta - \beta)
\]

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

At the second stage, the sub-module capacitance is no longer discharged due to the blocking of the inverter. The bridge arm inductance and the ac side power supply still feed current. Although the fault current formula at this stage is difficult to accurately express, the fault current at this stage still has an upward trend until it enters the steady-state stage.

To verify the above analysis, this paper uses the simulation model in Fig. 1 to obtain the fault current waveform as Fig. 2. The simulation results show that the faulty circuit oscillates in the initial stage of the fault (1.5s-1.53s).

\[\text{FIGURE 2. The current waveform on both sides of an internal fault.}\]

In summary, the fault current of the mmc-HVdc transmission line has an oscillation phenomenon.

### B. ANALYSIS OF FREQUENCY CHARACTERISTICS OF DISTRIBUTED CAPACITANCE CURRENT

This section analyzes the frequency characteristics of the fault current and proves that the high-frequency distributed capacitance current is the main cause of the fault current oscillation.

1) FREQUENCY CHARACTERISTICS OF FAULT CURRENT

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 (3) [23].

\[
f = \frac{1}{2\pi} \frac{1}{\sqrt{\frac{2L_0(3+\alpha L_0)N}{6C_0}} - \left(\frac{4R_f}{2L_0(3+\alpha L_0)}\right)^2}
\]

where $L_0$, $C_0$, $N$ are the bridge arm inductance, sub-module capacitance, and bridge arm sub-module number respectively; $x$, $L_{ai}$, $R_{ai}$ is the fault distance, unit inductance, and unit resistance respectively. According to the parameters (Appendix) of the model, the oscillation frequency of the fault current is about 52.6 Hz.

2) FREQUENCY CHARACTERISTICS OF DISTRIBUTED CAPACITANCE CURRENT

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 traveling wave. At this time, the theoretical minimum value of the fault current frequency as follows [24]:

\[
f_s = \frac{\nu}{4d}
\]

where $\nu$ is traveling wave velocity, $d$ 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 210km, the current frequency is 357Hz. Therefore, the frequency of the distributed capacitor current is greater than 357 Hz.

To verify the above analysis, the model in Fig. 1 is used as an example of simulation. Wavelet transform is used to analyze the fault information in this paper. Wavelet transform can decompose and reconstruct the signal in the frequency domain. Expand $\hat{x}(n)$ by spatial combination can get

\[
\hat{x}(n) = \sum_{j=-\infty}^{J} \sum_{k=-\infty}^{\infty} d_{j,k} \psi_{j,k}(t) + \sum_{k=-\infty}^{\infty} c_{j,k} \phi_{j,k}(t)
\]

where

\[
\begin{align*}
\psi_{j,k}(t) &= \frac{1}{\sqrt{2^{j/2}}} \psi\left(2^{j/2} - t\right) \\
\phi_{j,k}(t) &= \frac{1}{\sqrt{2^{j/2}}} \phi\left(2^{j/2} - t\right)
\end{align*}
\]

The first part of (5) is the projection of the signal in wavelet space, and the second part is the projection of the signal in scale space. $c_{j,k}$ represent the scale coefficient and $d_{j,k}$ represent the wavelet coefficient. The calculation formula of the scale coefficient and wavelet coefficient is shown as:

\[
\begin{align*}
&c_{j,k} = \sum_{m} h_0(m-2k)c_{j,m} \\
d_{j,k} = \sum_{m} h_1(m-2k)c_{j,m}
\end{align*}
\]

where $h_0$ is the low-pass filter coefficient, $h_1$ is the high-pass filter coefficient. Therefore, $c_{j,k}$ represents the low-frequency band of the signal, and $d_{j,k}$ represents the high-frequency band of the signal.

Analysis of the influence of special frequencies on the above results:

1) When an internal fault occurs, the frequency of the current is affected by the electrical parameters and the fault distance according to (3). Since the electrical parameters of
different MMC-HVDC projects do not change much, the frequency is mainly affected by the fault distance \((x)\). When the fault distance is 2km, the frequency is 52.6Hz. If the fault distance is increased, the frequency will be smaller. Therefore, 52.6Hz is close to the maximum frequency at the time of the internal fault.

2) Besides, the lines of the MMC-HVDC projects are relatively short. For example, the line length of China’s Zhangbei HVDC Flexible Project does not exceed 250km, and its frequency is not less than 300Hz during external fault according to (4). Therefore, 357Hz is almost the minimum frequency during an external fault.

3) Therefore, the frequency of this article can meet the actual project. Of course, if the line length exceeds 1425km, the frequency of internal faults and external faults may overlap. The line lengths of existing MMC-HVDC projects are far less than this value.

In summary, the proposed protection principle may fail only when the line is longer than 1425km.

The sampling frequency of the signal is 12kHz. The signal is decomposed and reconstructed by wavelet transform in 4 layers. The frequency band range of each layer is shown as follows: \(d_1 = 3\sim 6\)kHz; \(d_2 = 1.5\sim 3\)kHz; \(d_3 = 0.75\sim 1.5\)kHz; \(d_4 = 0.375\sim 0.75\)kHz; \(a_4 = 0\sim 0.375\)kHz. Therefore, this paper uses (5) and (6) to process the signal to get a signal less than 357Hz \((a_4)\) and a signal greater than 357Hz \((d_1 + d_2 + d_3 + d_4)\).

Using the wavelet algorithm to extract the signal, the frequency distribution of the fault current is shown in Fig. 3. Comparing Fig. 3(b) and Fig. 3(c), it can be concluded that the distributed capacitance current is the main cause of the fault current oscillation.

In summary, the high-frequency distributed capacitor current is the main cause of the fault current oscillation and the main factor of the current differential protection delay.

Some literature [23] uses wavelet transform and other algorithms to extract signals of different frequencies to solve the distributed capacitance problem. However, it has problems such as complex algorithms, difficulty to extract frequency signals, and low reliability. This paper proposes a protection principle based on the time domain, which not only completely solves the problem of distributed capacitive current, but also uses the full current signal to ensure the reliability of the protection.

III. FAULT IDENTIFICATION PRINCIPLE BASED ON CURRENT INTEGRAL CROSS-ENTROPY

This section first introduces the theoretical derivation of charge filtering distributed capacitor current. Subsequently, the charge difference between the internal fault and the external fault is analyzed, and a method using cross-entropy to express the difference is proposed in this section.

This paper needs to use the filtering characteristics of the current integral, and the charge is the integration of the current over time. For ease of understanding, the charge is referred to as ‘current integral’ in the following.

A. CURRENT INTEGRAL ELIMINATES DISTRIBUTED CAPACITANCE CURRENT

1) ANALYZE THE FILTERING CHARACTERISTICS OF THE INTEGRAL FROM THE PHYSICAL MEANING

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 integral 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 integral to handle fault currents can minimize the effects of distributed capacitor currents, and eliminates the oscillation of fault current.

2) FORMULA DERIVATION OF INTEGRAL FILTERING CHARACTERISTICS

Define the current integral as \(Q\) according to (1) can get (7).

\[
Q = \int i(t)dt
\]

\[
= A\sqrt{\frac{C}{L}}(e^{-\sigma t}(- \sin(\omega t + \theta) - \cos(\omega t + \theta)) + M)
\]

where

\[
A = \sqrt{U_0^2 + \left(\frac{U_0 \delta}{\omega L} - \frac{U_0}{\omega C}\right)^2}
\]

\[
\theta = \arctan\left(\frac{U_0 \delta}{\omega L} - \frac{U_0}{\omega C}\right)
\]

\[
\beta = \arctan\left(\frac{\omega C}{\delta R}\right)
\]

\[
\sigma = R/2L; \omega = \sqrt{1/LC - [R/2L]^2}
\]

**FIGURE 3.** Frequency characteristics of fault current: (a) original waveform of the fault current, (b) distributed capacitance current (greater than 357Hz), (c) fault current after filtering the distributed capacitance (less than 357Hz).
It can be seen from (5) that 

\[ e^{-\sigma t}(-\sin(\omega t + \theta - \beta) - \cos(\omega t + \theta - \beta)) \]

represents the oscillation part of the fault current integral. Therefore, only need to analyze the frequency characteristics of the current integral. Laplace transform can get its frequency domain formula as shown in (8).

\[ e^{-\sigma t}(-\sin(\omega t + \theta - \beta) - \cos(\omega t + \theta - \beta)) = -\left( \frac{\omega + s + \sigma}{(s + \sigma)^2 + \omega^2} \right) \]

It can be seen from (7) and (8) that the absolute value of the current integral decreases as the frequency of the signal increases. Therefore, integration can filter out high-frequency signals.

In summary, Section III-A proves the ability of the current integral to filter out high-frequency signals through physical meaning analysis and formula derivation. Therefore, this paper uses the current integral to filter out distributed capacitance currents and constructs fault identification criteria based on it.

**B. FAULT CURRENT INTEGRAL CHARACTERISTICS**

The two curves in Fig. 2 are the fault current waveforms, so the current integral is the vector value of the area enclosed by the time axis of the fault current curve, \( y = 0 \), and \( x = 0 \).

The analysis of current integral by fault current is shown 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, 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 integral 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 integral between internal and external faults. The fault current integral characteristics are summarized in Table I (“+” represents increase, “-” represents decrease). To express the current integral change trend, this paper proposes to use cross-entropy as a tool to measure the current integral change trend.

**C. CROSS-ENTROPY THEORY**

Cross-entropy is an important concept in Shannon’s information theory, which is mainly used to measure the difference information between two probability distributions [24]. In information theory, cross-entropy represents two probability distributions \( P, Q \). Where \( P \) represents the true distribution and \( Q \) represents the non-true distribution.

For discrete variables, the formula for cross-entropy is shown in (9).

\[ H(P, Q) = \sum_{x_1, \cdots, x_n} P(x) \log \frac{1}{Q(x)} \]

When (9) is used to process the current integral, \( x_1, \cdots, x_n \) represents the instantaneous value of the current, while \( P(x) \) and \( Q(x) \) represents the current integral on both sides. Cross-entropy quantifies the "distance" of two current integrals, but its distance does not represent the true length distance. It is a description of the similarity of the probability distribution of two current integrals. The smaller the cross-entropy, the higher the similarity between the two waveforms. Therefore, \( H = 1 \) represents the signals are the least similar; \( H = 0 \) represents the signals are the most similar. Also, the cross-entropy calculation process of the current integral is shown as follows:

1) Extract the fault currents on both sides and calculate the current integrals \( P(x) \) and \( Q(x) \) respectively.
2) Pretreatment of \( P(x) \) and \( Q(x) \). If \( Q(x) \) is a non-positive number, \( P(x) \) and \( Q(x) \) are converted to their opposite numbers respectively. If \( Q(x) \) is non-negative, then \( P(x) \) and \( Q(x) \) unchanged.
3) Put \( P(x) \) and \( Q(x) \) into formula (9) to get the cross-entropy.

According to Table I and (9), this paper uses the cross-entropy of the current integral to construct the protection criterion, which is described in detail as follows:

At the moment of a line fault, the cross-entropy of the current integral is calculated. If the cross-entropy is 0, it means that the current integral at the time of the fault has the same trend as the normal state. If the cross-entropy is 1, it means the changing trend is the opposite. However, the above analysis ignores the influence of measurement error, communication delay and noise interference. In order to correctly select the threshold, the analysis of the above three influencing factors is shown as follows:

1) Measurement error: the current signal in the actual project is obtained through a current transformer. Improper installation of the measuring device, environmental factors, and residual magnetic factors will

---

**TABLE I. Fault current integral characteristics.**

| Condition       | Positive pole | Negative pole |
|-----------------|---------------|---------------|
|                 | M terminal    | N terminal    |
| Normal          | +             | -             |
| Internal fault  | +             | +             |
| External fault  | +/-           | +/-           |
|                 | +/-           | +/-           |

---
cause measurement errors of the current transformer. However, the error of the current transformer is no more than 10% according to the technical requirements of the protective current transformer [23].

2) Communication delay: mmc-HVdc systems often use optical fiber communication and its speed is 200km/ms [24]. Since the line length of the simulation system in this paper does not exceed 250km, the communication delay is less than 1.25ms.

3) Noise: the noise in the current signal is Gaussian distributed. It is generally believed that the signal-to-noise ratio (SNR) of 500kV lines shall not be lower than 17dB [23].

Therefore, the above factors are considered in this paper, and a lot of simulations are carried out. The simulation results are shown in the Appendix. The simulation results prove that the cross-entropy does not exceed 0.0931 in the strictest state (Measurement error is 10%, the communication delay is 1.25ms, SNR is 10dB). In summary, this paper sets the threshold of the cross-entropy to 0.1 to reduce the impact of various factors.

The fault identification criteria are summarized as follows:

\[
\text{Internal fault : } H < 0.1 \quad (10)
\]

IV. PROTECTION SCHEME PROCESS

The process of the proposed protection principle, including the starting element and the fault pole selection element, is described in detail in this section. Finally, the running time of the proposed protection principle is also analyzed.

A. STARTUP ELEMENT BASED ON CURRENT DIFFERENTIAL

The starting element of the proposed protection principle is \( \frac{dI}{dt} \). Under normal operating conditions, the amount of current mutation is very small (not considering power transfer). 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 paper as follows:

\[
| \frac{dI}{dt} | > k_{set} \quad (11)
\]

where \( k_{set} \) is the threshold set by considering factors such as harmonics and noise. According to actual engineering experience [23], \( i > 1.1I_n \) when the protection fault. \( I_n \) represents the rated current. The rated current of the simulation model in this paper is 0.5kA, so set \( k_{set} = 50 \) (Note that the unit of \( i \) is kA and the unit of \( t \) is ms). The operating condition of the starting element in the actual project is that \( \frac{dI}{dt} \) exceeds the threshold three times in a row.

B. 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 paper. Define the definite integral of the positive fault current as \( \bar{Q}_p \) and the definite integral of the negative fault current as \( \bar{Q}_n \). The definite integral of the fault current is the area of the graph enclosed by the current curve and the coordinate axis. The area method uses the ratio of the area (definite integral) of the positive and negative fault currents to select the fault pole. When a pole-to-ground fault occurs, the current 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 healthy pole. However, the change of the positive and negative fault currents during a pole-to-pole fault is the same, so the area ratio is close to 1. Therefore, the ratio of the definite integral of the fault current can select the fault pole. So the description of the fault selection criterion using the area method is shown as follows:

\[
\begin{align*}
\text{positive pole-ground fault : } & \frac{|\bar{Q}_p|}{|\bar{Q}_n|} > k_{set1} \\
\text{negative pole-ground fault : } & \frac{|\bar{Q}_p|}{|\bar{Q}_n|} < k_{set2} \\
\text{pole-pole fault : } & k_{set2} < \frac{|\bar{Q}_p|}{|\bar{Q}_n|} < k_{set1}
\end{align*}
\]

where \( k_{set1} \) and \( k_{set2} \) are the threshold of the fault pole selection scheme. The condition for setting the fault pole selection threshold is: when the slightest internal fault occurs, the fault pole selection element can act correctly. A large number of simulations have been carried out for positive ground faults with different fault distances and different fault resistances. The simulation results are shown in Table XII (Appendix). The simulation results show that \( k_{set1} = 8 \) is the smallest when a high-impedance fault occurs at the end of the line. Generally, the existing literature [21] often chooses 1.2~1.3 as the threshold to ensure the sensitivity of the faulty pole selection element. To balance sensitivity and reliability, this paper set a threshold of \( k_{set1} = 1.5 \). Similarly, this paper set a threshold of \( k_{set2} = 1/k_{set1} \approx 0.6 \).

C. DISCUSSION PROCESS OF PROTECTION SCHEME

According to the analysis in Section III and Section IV, the steps of the protection scheme are described in detail as follows. Also, the program flow chart is described as Fig. 4.

Step 1: First, the protection device performs a data acquisition program and calculates the current. Then, substitute the current into the startup 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 integral is calculated for the fault identification procedure and the fault pole selection procedure. In order to reduce the protection time, the fault identification program and the fault pole selection program are run simultaneously

Step 3: In the second step, if the result of the fault detection is an external fault, the program returns. If (10) and (12) both meet the conditions, the protection device selects the fault pole and sends an action signal. After the protective action signal is issued, the program ends.

D. DISCUSSION ON THE RUNNING TIME OF THE PROPOSED PROTECTION PRINCIPLE

The sampling frequency of this paper is 10kHz, and the data window time is 1ms. Therefore, the protection criterion can be obtained within 1ms (\( t_1 \)) 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 6.67ns because the system clock is 150MHz. According to (7) and (9), the clock period of the algorithm in this paper is less than 1000. Therefore, the calculation time of the algorithm is 

\[ t_s < 0.67 \mu s. \]

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 

\[ t_2 = 0.5ms \]

Moreover, consider other time factors such as photoelectric conversion delay and measurement delay. Because the above factors are on the microsecond level. So set \( t_3 = 0.1ms \) as the sum of other factors. Finally, the communication delay is an indispensable part of calculating the differential protection time. Many factors cause communication delays, such as Transmission media, digital equipment, converters. Therefore, the calculation formula of communication delay \( t_d \) is as follows:

\[ t_d = t_e + t_p + t_r \times n + t_0 \]

where \( t_e \) is the transmission delay of the equipment, which is related to the equipment and transmission speed grade, and its time does not exceed 0.1ms. \( t_p \) is the delay of terminal equipment, including Pulse Code Modulation multiplexer and connecting circuit. The delay generated by the Pulse Code Modulation terminal is about 600\( \mu \)s. The delay setting \( t_p = 1ms \) considering other factors. \( t_r \) is the delay of the multiplexer, and its value is 0.1ms. \( n \) is the number of light intervals. \( t_0 \) is the transmission delay of the signal, and its value is 4.9\( \mu \)s/km. Since the longest line in the model in Fig. 1 does not exceed 250km, set \( t_0 = 1.225ms \). Therefore, the communication delay can be calculated as:

\[ t_d < 0.1 + 1 + 0.5 + 1.225 = 2.825ms. \]

The standard for communication delay in China is no more than 5ms.

In summary, the operating time \( T \) that can be protected is as follows:

\[ T = t_1 + t_2 + t_3 + t_d \approx 4.425ms. \]

Compared with the action time of the existing backup protection (1100ms), the protection principle proposed in this paper has great advantages.

V. SIMULATION

The proposed protection is verified by simulation in this section. The simulation model used in this section comes from Section I, and the detailed parameters of the two-terminal simulation model are shown in the Appendix. The parameters of this simulation are set as follows: 1) The fault location is set at \( f_1, f_2 \) and \( f_3 \) of the line, the fault types are pole-to-ground fault and pole-pole fault. 2) The fault time is 1.5s-2.0s, and the sampling frequency is 10kHz. Through the simulation of different types and different influencing factors, the feasibility
FIGURE 7. Simulation results of external pole-pole fault: (a) Positive fault current, (b) Negative fault current, (c) Positive fault current integral, (d) Negative fault current integral.

FIGURE 8. Simulation results of internal pole-pole fault: (a) Cross-entropy (Fault identification), (b) Current integral ratio (Fault pole selection).

FIGURE 9. Simulation results of internal pole-pole fault (distributed capacitor): (a) Fault current, (b) Fault current integral, (c) Cross-entropy (Fault identification).

A. VERIFICATION OF THE CORRECTNESS OF THE PROPOSED PROTECTION PRINCIPLE

1) INTERNAL POLE-POLE FAULT

An internal pole-pole fault ($f_1$) is set in the Line1 at the 1.5s. The fault distance is 100km and the transition resistance is 0 Ω. To show the changing trend of fault current oscillation and current integral, this paper selects the fault waveform of 1.45-1.6s (the fault time is 1.5s). The simulation results are shown in Fig. 5.

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

and superiority of the protection scheme are verified in this section.

Also, Fig.5(c), (d) demonstrates that when an internal fault occurs, the positive current integral increases, and the negative current integral decreases. Therefore, the simulation results of the current integral are the same as the theoretical analysis in Section III. As a result, the simulation results in Fig. 5 verify the correctness of the theoretical analysis in Section II.

To verify the correctness of the protection, the fault identification element, and the fault pole selection element are shown in Fig. 6.

Fig. 6(a) shows that the cross-entropy ($H$) is always less than 0.1 within 1ms. At this time, the current waveforms on both sides have the highest similarity. According to Table I and (10), it can be judged that the internal fault occurred at this time. Fig. 6(b) shows that the current integral ratio of positive and negative is between 0.6 and 1.5. According to (12), it can be judged that internal pole-pole fault occurs at this time.

TABLE 2. Simulation results of Pole-to-ground fault.

| Fault type       | $H$  | $|Q_P|/|Q_N|$ |
|------------------|------|-------------|
| Internal fault   | 0.008| 10-15       |
| Positive-to-ground | 0.982| 10-18       |
| Reverse external fault | 0.971| 10-15       |
| Internal fault   | 0.015| 0.06-0.1    |
| Negative-to-ground | 0.991| 0.06-0.1    |
| Reverse external fault | 0.997| 0.06-0.1    |
TABLE 3. Comparison of the capability to withstand distributed capacitance.

| Distributed capacitance | Twice | 4times | 8times | tenfold |
|-------------------------|-------|--------|--------|---------|
| Current differential protection | ✓ | ✓ | ✓ | ✓ |
| Protection principle [20] | ✓ | ✓ | ✓ | ✓ |
| Proposed protection | ✓ | ✓ | ✓ | ✓ |

FIGURE 10. Simulation results of different fault resistance and different fault distance.

In summary, when an internal fault occurs, both the fault identification criterion and the fault pole selection criterion conform to the analysis in Section III and Section IV. Therefore, the proposed protection principle can accurately identify internal pole-to-pole faults.

2) EXTERNAL POLE-POLE FAULT

An external pole-pole fault occurs at the point $f_2$ at 1.5s. The fault distance is 10km to MMC2 and the transition resistance is 0 Ω. The measured currents and current integrated values on both sides of the line are shown in Fig. 7.

Fig. 7(a), (b) shows that the fault current still oscillates when an external fault occurs. The current integral in Fig. 7(c), (d) shows that integration can eliminate current oscillations. Besides, the current integral in Fig. 7(c), (d) indicates that when an external fault occurs, the current integral transformation trend of the M terminal and the N terminal does not change. The simulation results of fault current and fault current integral are consistent with the analysis in Section III.

Similarly, the cross-entropy ($H$) and current integral ratio of positive and negative is between 0.6 and 1.5 which meets the fault pole selection criterion (12). Therefore, the proposed protection principle can accurately identify external pole-to-pole faults.

3) POLE-TO-GROUND FAULT OF INTERNAL FAULT AND EXTERNAL FAULT

Also, the pole-to-ground fault is simulated in this paper. The simulation conditions are the same as above, and the simulation results are listed in Table II. The simulation results show that $H < 0.1$ (internal fault) and $H > 0.1$ (external fault). At this time, the fault pole selection components ($\frac{|\bar{Q}_p|}{|\bar{Q}_n|}$) all meet (12).

B. INFLUENCE OF DC LINE-DISTRIBUTED CAPACITANCE

The current integral 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 analyze the influence of the distributed capacitance, a distributed capacitive parameter of 8 times the original value is set (The original line parameters are listed in Table X and Table XI) in Line1, and the simulation result is shown as Fig. 9.

Fig. 9(a) shows that the transient current has a large fluctuation due to the increase of the distributed capacitance. At this time, the traditional backup protection may refuse to operate. However, the fault current integral waveform (Fig.9(b)) is relatively smooth, which means that the current ratio of positive and negative is between 0.6 and 1.5 which meets the fault pole selection criterion (12). Therefore, the proposed protection principle can accurately identify external pole-to-pole faults.
integral eliminates the oscillation of the waveform and suppresses the distributed capacitor current. The cross-entropy ($H$) in Fig. 9(c) still meets the fault identification criterion (9), so the protection can accurately identify the fault with 8 times the distributed capacitance.

The performance of the proposed protection and transient current differential protection is compared in Table III. The current differential protection accurate performance only when the distributed capacitance is less than 2 times. The protection principle of reference [20] can only withstand 4 times the distributed capacitance. However, the protection scheme proposed in this paper can operate normally and is not affected by distributed capacitors. Therefore, the proposed protection principle has advantages in withstanding distributed capacitance.

### C. INFLUENCE OF FAULT RESISTANCE AND FAULT DISTANCE

Different faults with different fault resistance and different fault distance on Line 1 ($f_1$, $f_2$, $f_3$) are simulated in this study to test the proposed protection scheme. The simulation results are shown in Fig. 10. It can be seen from Fig. 10 that the cross-entropy ($H$) is less than 0.1 for internal faults ($f_1$), and the cross-entropy ($H$) is greater than 0.9 for external faults ($f_2$, $f_3$). Therefore, the increase of fault distance ($X$) and fault resistance has less influence on cross-entropy.

Table IV shows that the fault resistance cannot affect the correct operation of the proposed protection scheme. The performance of the proposed protection is determined by cross-entropy and does not rely directly on the magnitude of the fault current. So the protection can work correctly in different fault resistance.

### D. INFLUENCE OF NOISE

The noise signal is a kind of interference source generated inside the device or system. The SNR is often used to indicate the relationship between the normal signal and the noise signal. The smaller the SNR, the stronger the noise signal. Noise interference is one of the important problems that the protection scheme needs to solve. To verify the proposed

| Noise | 40dB | 30dB | 20dB | 10dB |
|-------|------|------|------|------|
| Current differential protection | √ | √ | × | × |
| Protection principle [20] | √ | √ | √ | × |
| Proposed protection | √ | √ | √ | √ |
| Protection principle [19] | √ | √ | × | × |

Table V 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 reference [19] can withstand a fault resistance of 1000Ω, while the reference [20] can only withstand a fault resistance of 400Ω. 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 principle uses the current integral as the characteristic value to expand the fault characteristics, and the impact of the current amplitude drop is weakened. Therefore, the proposed protection principle has a strong ability to withstand fault resistance.

### TABLE 6. Capability to noise in internal fault.

| Noise | 40dB | 30dB | 20dB | 10dB |
|-------|------|------|------|------|
| Current differential protection | √ | √ | × | × |
| Protection principle [20] | √ | √ | √ | × |
| Proposed protection | √ | √ | √ | √ |
| Protection principle [19] | √ | √ | × | × |

### TABLE 7. Test of the capability to withstand fault resistance.

| Fault type | Delay(ms) | $H$ | Result |
|------------|-----------|-----|--------|
| Internal   | 0.0       | 0.0185 | √     |
|            | 0.5       | 0.0651 | √     |
|            | 1.0       | 0.0823 | √     |
| External   | 0.0       | 0.9993 | ×     |
|            | 0.5       | 0.9834 | ×     |
|            | 1.0       | 0.9734 | ×     |

### TABLE 8. Comparison of communication synchronization requirements.

| Communication delay/ms | 0.3 | 0.5 | 1.5 |
|------------------------|-----|-----|-----|
| Protection principle [19] | √ | × | × |
| Proposed protection | √ | √ | √ |
| Protection principle [20] | √ | × | × |
method considering noise, 10dB∼40dB of noise is superimposed on measurements of each test. The probability distribution function of the noise is shown as (13). The mathematical expectation ($\mu_1$) is 0, and the variance of the Gaussian distribution ($\sigma_1$) is 1.

$$P_1(x) = \frac{1}{\sqrt{2\pi \sigma_1}} e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}}$$ (14)

The simulation results are shown in Fig.11.

To prove the superiority of the proposed protection principle in anti-noise interference, white noise with different SNR is added to the traditional protection principle and the proposed protection principle respectively. The simulation results are listed in Table VI. As shown in Table VI, the current differential protection can operate under 30dB noise interference while the protection principle based on current correlation [20] can operate under 20dB noise interference. Notably, only the proposed protection operated correctly under 10dB noise.

### E. INFLUENCE OF COMMUNICATION DELAY

Communication delay is a problem that cannot be ignored for protection. DC protection often uses optical fiber transmission and its speed is 200 km/ms. Since the line length of the simulation system in this paper does not exceed 250km, the communication delay is less than 1.25ms. Besides, the time window of the proposed protection principle is 1ms.

### F. INFLUENCE OF LOAD VARIATIONS

Load variations affect the protection principle by changing the magnitude of the fault current. However, the proposed protection principle has the following advantages: 1) The use
of integral can amplify the characteristics of fault information and reduce the influence of fault current changes. 2). The proposed protection principle uses the current integral to eliminate the influence of distributed capacitor current and solve the long delay problem of current differential protection.

To verify the above analysis, different loads are used in the simulation. The simulation result is shown in Fig. 12. The simulation result shows that the cross-entropy is far less than 0.1. Therefore, the proposed protection principle is not affected by load variations.

G. APPLICABILITY ANALYSIS OF MULTI-TERMINAL DC NETWORKS

In order to verify the applicability of the proposed protection principle in a multi-terminal dc network, a four-terminal DC system model is used for simulation in this section. The simulation model is listed in the Appendix (Fig.14). Internal faults ($f_1$) and external faults ($f_2$) with different fault resistances, different noises, and different distributed capacitances are simulated, and the simulation results are listed in Table IX. The simulation results show that the proposed protection principle can be applied to a multi-terminal dc network.

VI. CONCLUSION

In this paper, a novel protection scheme based on the Cross-Entropy of charge is proposed to meet both the speed and selectivity requirement of mmc-HVdc line protection. The Cross-Entropy of charge (current integral) is used for fault identification (The Cross-Entropy of charge is 0 and 1 for internal faults and external faults, respectively). The advantages of the proposed protection principle are shown as follows:

1) The proposed protection principle uses the current integral to eliminate the influence of distributed capacitor current and solve the long delay problem of current differential protection.

2) Since the proposed protection principle only requires 1ms of communication and does not require strict communication synchronization, the communication burden of the system is reduced. Besides, the proposed protection principle is not only applicable to double-terminal dc systems but also multi-terminal dc networks.

3) Simulation results prove that the proposed protection principle can rapidly and accurately operate and tolerate the uncertainty caused by up to 1000Ω fault resistance, 10dB noise, and 1.5ms 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.

Also, the proposed protection principle belongs to the time domain analysis protection principle, which has the advantages of simple principle, easy application, high adaptability to different systems, and a good economy.

APPENDIX

The parameters of the mmc-HVdc system (Fig.1) are listed in Table X and Table XI. The equivalent circuit of the fault is shown in Fig. 13. The topology of the multi-terminal dc network is shown in Fig. 14. The simulation result of the
threshold of cross-entropy is shown in Fig. 15. The threshold of fault pole selection is listed in Table XII.

REFERENCES

[1] Y. Wang, Q. Song, and Q. Sun, “Multilevel MVDC link strategy of high-frequency-link DC transformer based on switched capacitor for MVDC power distribution,” IEEE Trans. Ind. Electron., vol. 64, no. 4, pp. 2829–2835, Jan. 2017.

[2] Y. Chen, R. Moreno, G. Srirac, and D. Alvarado, “Coordination strategies for securing AC/DC flexible transmission networks with renewables,” IEEE Trans. Power Syst., vol. 33, no. 6, pp. 6309–6320, Nov. 2018.

[3] N. Yousefpoor, A. Narwal, and S. Bhattacharya, “Control of DC-Fault-Resilient voltage source converter-based HVDC transmission system under DC fault operating condition,” IEEE Trans. Ind. Electron., vol. 62, no. 6, pp. 3683–3690, Jun. 2015.

[4] D. Van Herten and M. Ghandhari, “Multi-terminal VSC HVDC for the European supergrid: Obstacles,” Renew. Sustain. Energy Rev., vol. 14, no. 9, pp. 3156–3163, Dec. 2010.

[5] R. Ara, U. A. Khan, A. I. Bhatti, and B. W. Lee, “A reliable protection scheme for fast DC fault clearance in a VSC-based meshed MTDC grid,” IEEE Access, vol. 8, pp. 88188–88199, 2020.

[6] X. Pei, H. Pang, Y. Li, L. Chen, X. Ding, and G. Tang, “A novel Ultra-High-Speed traveling-wave protection principle for VSC-based DC grids,” IEEE Access, vol. 7, pp. 119765–119773, 2019.

[7] X. Huang, L. Qi, and J. Pan, “A new protection scheme for MMC-based MVdc distribution systems with complete converter fault current handling capability,” IEEE Trans. Ind. Appl., vol. 55, no. 5, pp. 4515–4523, Sep. 2019.

[8] J. Sneath and A. D. Rajapakse, “Fault detection and interruption in an earthed HVDC grid using ROCOV and hybrid DC breakers,” IEEE Trans. Power Del., vol. 31, no. 3, pp. 973–981, Jun. 2016.

[9] K. D. Kerf, K. Srivastava, and D. V. Herten, “Wavelet-based protection strategy for DC faults in multi-terminal VSC-HVDC systems,” IET Gener. Transm. Distrib., vol. 5, pp. 496–503, Apr. 2011.

[10] Z. Zheng, T. Tai, J. S. Thorp, and Y. Yang, “A transient harmonic current protection scheme for HVDC transmission line,” IEEE Trans. Power Del., vol. 27, no. 4, pp. 2278–2285, Oct. 2012.

[11] G. Song, X. Chu, S. Gao, X. Kang, and Z. Jiao, “A new whole-line quick-action protection principle for HVDC transmission lines using one-end current,” IEEE Trans. Power Del., vol. 30, no. 2, pp. 590–607, Apr. 2015.

[12] X. Liu and A. H. Osman, “Hybrid traveling wave/boundary protection for monopolar HVDC line,” IEEE Trans. Power Del., vol. 24, no. 2, pp. 569–578, Jul. 2009.

[13] B. Mitra, B. Chowdhury, and A. Willis, “Protection coordination for assembly HVDC breakers for HVDC multiterminal grids using wavelet transform,” IEEE Syst. J., vol. 14, no. 1, pp. 1069–1079, Mar. 2020.

[14] M. E. Baran and N. R. Mahajan, “Overcurrent protection on Voltage-Source-Converter-Based multiterminal DC distribution systems,” IEEE Trans. Power Del., vol. 22, no. 1, pp. 406–412, Jan. 2007.

[15] W. Chen, O. P. Malik, X. Yin, D. Chen, and Z. Zhang, “Study of wavelet-based ultra high speed directional transmission line protection,” IEEE Trans. Power Del., vol. 18, no. 4, pp. 1134–1139, Oct. 2003.

[16] X. Liu, A. H. Osman, and O. P. Malik, “Real-time implementation of a hybrid protection scheme for bipolar HVDC line using FPGA,” IEEE Trans. Power Del., vol. 26, no. 1, pp. 101–108, Jan. 2011.

[17] S. Biswal, M. Biswal, and O. P. Malik, “Hilbert huang transform based online differential relay algorithm for a shunt-compensated transmission line,” IEEE Trans. Power Del., vol. 33, no. 6, pp. 2803–2811, Dec. 2018.

[18] X. Min, C. Zexiang, H. Kunlun, and Z. Yongjun, “A sensitive and high-speed traveling wave protection scheme for HVDC transmission line,” Int. Trans. Elect. Energy Syst., vol. 25, no. 3, pp. 393–404, Mar. 2015.

[19] W. Yanting, H. Zhiguo, and X. Baphui, “A pilot protection scheme for transmission lines in VSC-HVDC grid based on similarity measure of traveling waves,” IEEE Access, vol. 7, pp. 7147–7158, 2019.

[20] K. Jia, C. Wang, and T. Bi, “Transient current waveform similarity based protection for flexible DC distribution system,” IEEE Trans. Ind. Electron., vol. 66, no. 12, pp. 9301–9311, Jul. 2019.

[21] B. Li, Y. Li, J. He, and W. Wen, “A novel single-ended Transient-Voltage-Based protection strategy for flexible DC grid,” IEEE Trans. Power Del., vol. 34, no. 5, pp. 1925–1937, Oct. 2019.

[22] J. Yang, J. E. Fletcher, and J. O’Reilly, “Short-circuit and ground fault analyses and location in VSC-based DC network cables,” IEEE Trans. Ind. Electron., vol. 59, no. 10, pp. 3827–3837, Oct. 2012.

[23] M. Li, “Study on protection of VSC-DC distribution system,” Ph.D. dissertation, Elect., Eng., Nor Ch Ele Power Univ., Beijing, China, 2018.

[24] Y. Ho and S. Wookey, “The Real-World-Weight cross-entropy loss function: Modeling the costs of mislabeling,” IEEE Access, vol. 8, pp. 4806–4813, 2020.