Research on the protection scheme of MMC-MTDC based on high frequency energy

Shimin Xue | Shuo Chen | Yabing Sun | Cheng Gu | Baibing Liu

Abstract
The development of flexible HVDC transmission technology requires the improvement of the theory of relay protections. The protection method based on the time domain has poor resistance to transition resistance and is easily affected by interference factors. The protection based on frequency domain analysis can better reflect the essential characteristics of the fault, and it is also an urgent problem for relay protections. The blocking effect of boundary elements on both sides of the line on high-frequency components is an important entry point for current protection research, but high-frequency protections are very sensitive to noise signals. Therefore, this paper analyses the frequency characteristics of the voltage at the measuring point from the perspective of the traveling wave transmission process, and uses the S transform to design a protection method based on high-frequency energy to realize the identification of internal and external faults. Finally, the ability to withstand transition resistance and anti-noise of the protection proposed here is verified by using PSCAD/EMTDC. The protection can complete fault identification within 2 ms, which means that it has both reliability and quick action.

1 | INTRODUCTION

Compared with line commutated converter based high voltage direct current (LCC-HVDC), voltage source converter based high voltage direct current (VSC-HVDC) has better operating performance. The emergence of modular multilevel converter (MMC) has promoted the development of VSC-HVDC [1]. However, the development of modular multilevel converter based HVDC (MMC-HVDC) needs to improve the corresponding relay protection theory to ensure the reliable removal of DC side faults.

At present, the protection based on traveling waves is used as the main protection in actual projects. However, the wave head of the traveling wave will be affected by the attenuation of the line and the transition resistance, which will affect the sensitivity of the protection [2–4]. At the same time, when the fault distance is too short, the traveling wave head is not easy to capture due to the limitation of the sampling frequency. Pilot protections have very good reliability, and are generally used as the main protection in the AC system. Literature [5] uses the amplitude of the anti-traveling waves at both ends to identify faults, and literature [6] constitutes a pilot protection scheme based on the relationship between the voltage and current at both ends of the line. Literature [7, 8] considers the distribution parameters of the line to improve the accuracy of pilot protections. However, in long-distance DC transmission projects, protections based on double-ended quantities cannot be used as the main protection due to communication delay. The special physical elements at both ends of the line can provide natural boundary conditions for protections, such as the DC filter in the traditional DC system, the large capacitor on the DC side in the VSC-HVDC system, and the current-limiting reactor on the line in the MMC-HVDC system. Therefore, the research on the characteristics of the components can provide an important theoretical basis for the formulation of protection schemes [9, 10]. Literatures [11, 12] use the voltage change rate of the measuring point and the current-limiting reactor voltage to identify the internal and external faults, but they are susceptible to the influence of the transition resistance. Compared with time domain protections, frequency domain protections have higher resistance to transition resistance. Literatures [13–15] use the attenuation effect of boundary elements on high frequency energy to realize the identification of internal and external faults.
components to form high frequency protections, but they are susceptible to noise interference.

As a brand-new frequency domain analysis method, S transform can overcome the shortcoming of short-time Fourier transform that the resolution cannot be dynamically transformed due to the constant size of the window function, and the shortcoming of wavelet transform that scale and frequency cannot correspond [16].

This article analyses the frequency characteristics of the voltage at the measuring point from the perspective of traveling waves, and constructs a protection criterion with high-frequency energy. According to the characteristics of the power spectral density of Gaussian white noise, the noise identification criterion is constructed based on the S transform. It is verified by simulation that the proposed protection has extremely high tolerance to transition resistance and noise, and can identify the fault within 2 ms.

2 SYSTEM STRUCTURE OF MMC-MTDC

Figure 1 shows the topology of a four-terminal flexible DC transmission system. On the DC side, overhead lines are used to form a loop power transmission network, and both ends of the line are connected with a DC circuit breaker and a current-limiting reactor. All four converter stations are connected to the grounding point through metal loops. The internal topology of the converter station is shown in Figure 2. The converter station adopts symmetrical bipolar wiring, and the grounding outlet is connected with a current-limiting reactor. The metal loop is drawn from the middle of the two converters. In addition, the converter sub-modules are all common half bridge structure.

3 FREQUENCY CHARACTERISTICS OF THE FAULT VOLTAGE

3.1 Fault in the line area

When the DC line fails, the fault point will generate voltage traveling waves transmitted to both ends of the line. The value of the initial voltage traveling wave is related to the working voltage during normal operation at the fault point. From the perspective of the frequency domain, the fault traveling wave has a wide frequency band. When the initial traveling wave propagates to the protection installation, each frequency component will be attenuated to different degrees. When the positive line fails, the equivalent circuit is shown in Figure 3. \( C_{eq} = 6C_0/N, L_{eq} = 2L_{arm}/3 \) are the equivalent capacitance and equivalent inductance of the converter respectively, and their specific parameters are shown in Table 1 below. \( Z_e \) is the characteristic impedance of the line. When considering the frequency variation characteristics of the line, it is a function of frequency [17]. \( \Delta U_{fp} \) is the initial value of the voltage step signal at the fault point.

| Converter stations | A   | B   | C   | D   |
|-------------------|-----|-----|-----|-----|
| Capacity/ MW      | 3000| 3000| 1500| 1500|
| Number of submodules | 20  | 20  | 20  | 20  |
| Sub-module capacitance/mF | 1.23 | 1.23 | 0.666 | 0.666 |
| Arm inductance /mH | 50  | 50  | 100 | 100 |
| Transformer rated transformation ratio | 500/260 | 500/260 | 230/260 | 230/260 |
| Current-limiting reactor /mH | 150 | 150 | 150 | 150 |
The voltage of the measuring point $\Delta U_{mp}$ can be expressed as:

$$\Delta U_{mp}(f) = \Delta U_{fp}(f) \cdot A(f) (1 + \rho_m(f))$$ (1)

$\rho_m(f)$ is the reflection coefficient of the traveling wave at the protection installation.

$$\rho_m(f) = \frac{Z_{sn}(f) - Z_s(f)}{Z_{sn}(f) + Z_s(f)}$$ (2)

And:

$$Z_{sn}(f) = j2\pi f(L_{eq} + L_4) - j \frac{1}{2\pi f C_{eq}}$$ (3)

It can be seen from Figure 4 that the DC side impedance $Z_{sn}$ has a high resistance value at high frequencies, while the characteristic impedance of the line is generally several hundred ohms, that is, the high frequency component of the fault traveling wave is approximately totally reflected at the protection installation. Then $\Delta U_{mp}(f)$ can be expressed as:

$$\Delta U_{mp}(f) = 2\Delta U_{fp}(f) A_f(f)$$ (4)

$A_f(f)$ is the line attenuation function when the distance from the fault point to the protection installation is $d$, and the total length of the line is $l$.

3.2 Fault out of the line area

When a ground fault occurs on the positive bus on the opposite side of the line, the equivalent circuit of the fault is shown in Figure 5.

$Z_{sn}$ is the equivalent impedance of the n-side system. At this time, the voltage at the protection installation $\Delta U_{mp}^1(f)$ can be expressed as:

$$\Delta U_{mp}^1(f) = \frac{2\Delta U_{fp}(f) A_f(f) Z_s(f)}{j2\pi f L_{dc} + Z_s(f)}$$ (5)

When a ground fault occurs on the positive bus on the back side of the protection, the equivalent circuit of the fault is shown in Figure 6.

The voltage at the protection installation $\Delta U_{mp}^2(f)$ can be expressed as:

$$\Delta U_{mp}^2(f) = \frac{\Delta U_{fp}(f) Z_s(f)}{j2\pi f L_{dc} + Z_s(f)}$$ (6)

3.3 Analysis of fault characteristics

Since the farther the fault point is, the smaller the line attenuation function, so $|A_f(f)| > |A_i(f)|$. According to Equations (4) and (5), it can be seen that $|\Delta U_{mp}^1(f)| < |\Delta U_{mp}(f)|$, that is, the amplitude of the high-frequency component of the fault in the line area is greater than that of the fault outside the forward area.

The voltage at the fault point $\Delta U_{fp}$ can be decoupled into a 0-mode component and a 1-mode component.

$$\begin{bmatrix} \Delta U_{F0}(f) \\ \Delta U_{F1}(f) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \Delta U_{fp}(f) \\ \Delta U_{fa}(f) \end{bmatrix}$$ (7)
The 0 mode voltage and 1 mode voltage at the protection installation can be expressed as:

$$\begin{align*}
\Delta U_{m0}(f) &= 2U_{F0}(f)A_{d0}(f) \\
\Delta U_{m1}(f) &= 2U_{F1}(f)A_{d1}(f)
\end{align*}$$

(8)

The positive and negative voltages at the protection installation can be expressed as:

$$\left[ \begin{array}{c} 
\Delta U_{mp}(f) \\
\Delta U_{mn}(f)
\end{array} \right] = \frac{1}{\sqrt{2}} \left( \begin{array}{cc}
1 & 1 \\
1 & -1
\end{array} \right) \left[ \begin{array}{c} 
\Delta U_{m0}(f) \\
\Delta U_{m1}(f)
\end{array} \right]$$

(9)

Since $\Delta U_{mp}(f) \approx 0$ when the positive line fails, $\Delta U_{F0}(f) \approx \Delta U_{F1}(f)$. By Equations (4), (7)–(9), we can get:

$$\Delta U_{mp}(f) = \Delta U_{mp}(f)(A_{d0}(f) + A_{d1}(f))$$

(10)

According to the Marti model, $Z_{mp}(t)$ and $P_{s}(t)$ are used to fit the characteristic impedance and the propagation function when the end of the line fails [18]. Figures 7 and 8 are respectively the fitting diagrams of the characteristic impedance and the propagation function of the line. The fitting forms are as follows:

$$Z_{mp}(t) = k_0 + \sum_{i=1}^{n} \frac{k_i}{s + p_i}$$

(11)

$$P_{s}(t) = \sum_{i=1}^{n} \frac{k_i}{s + p_i}$$

(12)

Make $x_1(f) = A_{d0}(f) + A_{d1}(f), x_2(f) = |Z_{c1}(f)|/(2\pi fL_{dc} + Z_{c1}(f)).$ Then:

$$|\Delta U_{mp}^2(f)| = \left| \frac{\Delta U_{mp}(f)Z_{c1}(f)}{2\pi fL_{dc} + Z_{c1}(f)} \right| < |\Delta U_{mp}(f)x_2(f)|$$

(13)

Figure 9 shows the waveforms of functions $x_1(f), x_2(f)$ and $x_1(f)/x_2(f)$.

It can be seen that $x_1(f)/x_2(f) \gg 1$, so $|\Delta U_{mp}^2(f)| < |\Delta U_{mp}(f)|$. And it has a maximum value at 50000 Hz.

In summary, the amplitude of high-frequency of internal faults is greater than that of external faults. For a symmetrical bipolar system, a bipolar fault can be regarded as a unipolar grounding fault of both positive and negative poles. Therefore, the analysis method of negative grounding and bipolar faults is similar to that of positive pole faults. The selection of the fault pole can be judged according to the change of the 0-mode component:

$$\Delta U_{m0} = \frac{1}{\sqrt{2}}(\Delta U_{mp} + \Delta U_{mn})$$

(14)

When the positive pole fails, $\Delta U_{m0} < 0$. When the negative pole fails, $\Delta U_{m0} > 0$. In the case of a bipolar fault, $\Delta U_{m0} \approx 0$.

### 4 | BASIC PRINCIPLES OF S TRANSFORMATION

The 1D continuous S transform of the signal $x(t)$ can be defined as:

$$S(\tau, f) = \int_{-\infty}^{\infty} x(t)\omega(\tau - t, f) \exp(-2\pi jft)dt$$

(15)

$\omega(\tau - t, f)$ is the Gaussian window function. When the frequency is high, the window length is short and has a high time resolution. On the contrary, when the frequency is low, the window length is long and has a high frequency resolution.

$$\omega(\tau - t, f) = \frac{1}{\sqrt{2\pi}} \exp\left(-j\frac{\tau^2}{2}\right)$$

(16)
FIGURE 9 The waveforms of functions $x_1(f)$, $x_2(f)$ and $x_1(f)/x_2(f)$

The discrete S transform of the signal $x(t)$ can be obtained from its discrete Fourier transform, and the discrete Fourier transform of $x(t)$ can be expressed as $X[n NT]$:

$$X \left[ \frac{n}{NT} \right] = \frac{1}{N} \sum_{k=0}^{N-1} x(kT) \exp \left( -\frac{2\pi jnk}{N} \right)$$

(17)

where $N$ is the number of sampling points, $T$ is the sampling period. Therefore, $k = 0, 1, 2 \cdots, N - 1$. $n$ is affected by the sampling frequency. Consequently, according to the Nyquist theorem, $n = 0, 1, 2 \cdots, N/2$, and $n = 0$ represents the DC component. The discrete S transformation of the signal $x(t)$ can be defined as:

$$S \left( \frac{n}{NT}, bT \right) = \sum_{n=0}^{N-1} x(kT) \exp \left( -\frac{2\pi jmk}{N^2} \right) \exp \left( \frac{2\pi jbm}{N} \right)$$

(18)

$$S(0, bT) = \frac{1}{N} \sum_{k=0}^{N-1} x(kT) \delta(k)$$

(19)

It can be seen that the signal obtained from the discrete S transformation is a plural matrix. In this matrix, the rows correspond to different discrete frequencies, and the columns correspond to different discrete times. And the frequency difference between rows is $1/NT$, the time difference between columns is $T$.

5 | GAUSSIAN WHITE NOISE

The noise problem has always been the most important interference factor in the research of protection schemes. When the noise content is large, it may cause protection misoperation or misjudgment. Therefore, studying the time-frequency regularity of noise is of great significance to improving the reliability of protection.

Gaussian white noise has the characteristics that the instantaneous value obeys the Gaussian distribution, and the power spectral density obeys the uniform distribution [19]. The strength of the noise signal is usually expressed by the signal-to-noise ratio (SNR), and the unit of measurement for SNR is dB. Assuming that $V_s$ and $V_n$ represent the effective voltage values of the real signal and the noise signal, respectively, the SNR of a mixed signal is defined as:

$$\text{SNR} = 20 \log(V_s/V_n)$$

(20)

The power spectral density is defined as the signal power in the unit frequency band, which represents the change of signal power with frequency, that is, the distribution of signal power in the frequency domain. The power spectrum represents the relationship between signal power and frequency. Moreover, the Wiener–Shinchin theorem states: the power spectral density of a signal is the Fourier transform of the autocorrelation function of the signal [20]. If $\sigma^2$ represents the variance of the noise signal, the autocorrelation coefficient $R(t)$ and power spectral density of Gaussian white noise $P(f)$ can be expressed as:

$$R(t) = \sigma^2 \delta(t)$$

(21)

$$P(f) = \sigma^2 \left( -\frac{f_s}{2} \leq f \leq \frac{f_s}{2} \right)$$

(22)

It can be seen from Figure 10 that the power spectral density obeys a uniform distribution in the frequency domain. If S transform is used to find the power spectral density of noise, the distribution of power spectral density with frequency will be
6.1 Protection start

The starting criterion should ensure the starting sensitivity of the protection. When a fault occurs, the fault voltage traveling wave will propagate to both sides of the line. After a short transmission delay of traveling wave, the voltage at the measuring point will drop rapidly. Therefore, considering the DC voltage fluctuation during normal operation, this article defines the deviation voltages $\Delta U_1, \Delta U_2$ and the normal stable voltage $U_a$:

$$
\begin{align*}
\Delta U_1 &= u_j(k) - U_a \\
\Delta U_2 &= u_j(k+1) - U_a
\end{align*}
$$

(24)

In Figure 11, it can be seen that the power spectral density of Gaussian white noise under S transform gradually increases with frequency.

$$
U_a = \frac{1}{20} \sum_{i=1}^{20} u_j(k-i)
$$

(25)

where $j = p, n$, it represents the voltage of the positive or negative measuring points. $u_j(k)$ is the value of voltage at the current sampling moment. When the voltage value at two consecutive sampling moments deviates greatly from the normal stable voltage, it can be considered that a fault may have occurred:

$$
\Delta U_1 < U_{set} \& \Delta U_2 < U_{set}
$$

(26)

$\Delta U_{set}$ is the start threshold of protection, which is determined according to the deviation voltage during normal operation.
6.2 | Fault determination

In this paper, the fault pole is judged based on the change trend of the 0-mode component. When this pole has a ground fault or bipolar fault, the protection of this pole should be activated

$$k_0 = \frac{1}{10} \sum_{i=1}^{10} (\Delta U_{m0}[i + 1] - \Delta U_{m0}[i])$$

(27)

$$\begin{aligned}
&\left\{ \begin{array}{ll}
k_0 < k_{set} & \rightarrow (PG, PN) \\
k_{set} < k_0 & \rightarrow (NG)
\end{array} \right.
\end{aligned}$$

(28)

From the previous analysis, it can be seen that there are huge differences in the amplitude of the high-frequency components of the faults inside and outside the area. In this paper, the S transform is used to extract the components of the measured voltage from 19,000–20,000 Hz to form the frequency energy $W_1$.

$$W_1 = \sum_{j=1}^{y_1} \sum_{k=1}^{n} S_x[j, k] S^*_x[j, k]$$

(29)

$j_1, y_2$ are the corresponding rows of frequency components of 19,000 and 20,000 Hz in $S_x$, and $n$ is the number of data. When $W_1 > W_{set}$, it can be considered that a fault in the zone may has occurred.

6.3 | Identification of noise interference

The noise signal also contains high-frequency components with high amplitude, but its power spectral density under S transform is proportional to the frequency, so this feature can be used to distinguish them. Define $W_2$ as the high frequency energy of 1000–2000 Hz:

$$W_2 = \sum_{j=1}^{y_3} \sum_{k=1}^{n} S_x[j, k] S^*_x[j, k]$$

(30)

$j_3, y_4$ are the corresponding rows in $S_x$ for the frequency components of 1000 and 2000 Hz. Assuming that the power spectral density of noise is $E_S = k_0 f$, where $k_0$ is related to the variance of the noise signal. Then $W_1, W_2$ can be expressed as:

$$\begin{aligned}
&W_1 = \int_{5625}^{6875} k_q f df \\
&W_2 = \int_{10000}^{11250} k_q f df
\end{aligned}$$

(31)

Make:

$$\lambda_i = \frac{W_2}{W_1}$$

(32)

Solving Equations (31) and (32) can get $\lambda_i = 13$. In the case of a fault, the frequency components are mainly concentrated in the middle and low frequencies, which is completely different from the noise signal. When $\lambda_i > \lambda_{set}$, it can be considered as noise interference.

6.4 | Protection flow chart

The protection flow chart is shown in Figure 12.

7 | SIMULATION ANALYSIS

7.1 | Simulation parameters and protection related thresholds setting

In this article, the system of MMC-MTDC shown in Figure 1 is built in the PSCAD/EMTDC. The system voltage level is ±500 kV. Both the simulation step length and the sampling step length are 25 $\mu$s. The lines adopt frequency-dependent models. The relevant parameters of the system and lines are shown in Table 1 and Table 2.

In order to verify that the system can be used as a simulation verification, Figure 13 shows the voltage and current waveforms at the protective installation when a ground fault occurs at the midpoint of the positive line. It can be seen that the system enters a stable operation state after a certain period of time, and the fault occurs at 1.3 ms. At this time, the positive electrode voltage drops to 0 after oscillation, and the negative electrode voltage will also fluctuate due to the coupling. The
### TABLE 2 Parameters of lines

| Lines   | Line12 | Line23 | Line34 | Line41 |
|---------|--------|--------|--------|--------|
| length /km | 206.6  | 186.7  | 205.1  | 49.3   |
| Split number | 6      | 6      | 6      | 6      |
| DC Resistance /Ω/km | 0.321  | 0.321  | 0.321  | 0.321  |
| Soil resistance /Ω/km | \(1 \times 10^5\) | \(1 \times 10^5\) | \(1 \times 10^5\) | \(1 \times 10^5\) |

*FIGURE 13* The voltage and current waveforms at the protective installation when a ground fault occurs at the midpoint of the positive line

According to the sampling frequency and the length of the data window, \(S_x\) is a \(41 \times 80\) matrix. The protection only needs to calculate the required rows (3, 4, 5, 39, 40, 41) instead of calculating the entire matrix. In order to eliminate the error caused by the boundary effect of the S transform at the head and tail of the data window, this paper uses the 0.5 ms \((n = 20)\) data after the protection is activated to calculate \(W_1'\) and \(\lambda_s\). Set the \(W_{set}\) based on the maximum value of \(W_1'\) when there is a fault outside the zone and then take the reliability coefficient of 1.2. \(k_{set}\) should be able to accurately determine the fault pole. Therefore, \(W_{set} = 31.45\) MW and \(k_{set} = 10\) kV. Considering that \(k_q\) is not an absolute fixed value and the calculation deviation of Equation (29), take \(\lambda_{set} = 6.5\). The related algorithms of the protection of this paper are completed in an offline manner in MATLAB.

#### 7.2 Internal and external faults

*FIGURE 15* is diagrams of time-frequency distribution of the voltage at the measuring point during normal operation, line midpoint \(F_1\) failure, \(F_2\) failure and \(F_1\) failure (the window length used for drawing is 10 ms, and the sampling frequency is 40 kHz. The fault occurs at 1.3 ms). It can be seen that the voltage signal at the time of the fault contains abundant frequency components, and the amplitude of the high-frequency component is obviously different between the fault outside the zone and the fault inside the zone. Figure 15(b) has higher amplitude on both sides of the time axis, which is caused by the boundary effect of the S transform. In actual projects, some data at both ends of the data window should be discarded, or the time window should be smoothed.

The simulation results when faults occur at different positions of the line are shown in Table 3. It can be seen that the protection scheme can correctly distinguish the faults inside and outside the area, and \(\lambda_s\) is much smaller than \(\lambda_{set}\). It shows that the frequency components are mainly concentrated in the middle and low frequency when the fault occurs, and will not be confused with the noise signal.

#### 7.3 Transition resistance

In order to better verify the ability to resist transition resistance, this section compares the protection proposed in this paper with the existing typical protection schemes. Existing protection schemes are mainly divided into protections based on time domain and protections based on frequency domain. For time domain protection, we take the protections using the current rate of change and the voltage rate of change as examples. Other protection schemes that use reactor voltage, power, and impedance are essentially combinations of current and voltage. For frequency domain protection, we take wavelet transform as an example. The protection based on wavelet transform mainly extracts the high-frequency component of the fault voltage or current, so as to realize the identification of the protection inside and outside the area [13, 14]. The frequency component
FIGURE 15  Time–frequency distribution diagrams of measured voltage in different states

TABLE 3  Simulation results of different fault locations

| Fault location | Fault type | $\Delta U_1$/kV | $\Delta U_2$/kV | $k_0$ | $W_1$/MW | $\lambda_r$ | judgement result |
|----------------|------------|----------------|----------------|-------|----------|----------|-----------------|
| 0 km           | PG         | 486.523        | 486.523        | -409.29 | 12591.97 | 0.207     | fault           |
|                | NG         | 85.616         | 89.438         | 414.00  | /        | /         | normal          |
|                | PN         | 492.298        | 492.284        | 1.62   | 12921.21 | 0.209     | fault           |
| 50 km          | PG         | 179.395        | 671.922        | -602.77 | 2652.46  | 0.003     | fault           |
|                | NG         | 68.592         | 94.321         | 598.01  | /        | /         | normal          |
|                | PN         | 298.194        | 944.921        | -1.47  | 12035.60 | 0.010     | fault           |
| 103.3 km       | PG         | 68.084         | 431.327        | -496.21 | 1981.17  | 0.008     | fault           |
|                | NG         | 72.828         | 272.380        | 492.86  | /        | /         | normal          |
|                | PN         | 203.596        | 873.439        | 2.82   | 13805.35 | 0.035     | fault           |
| 206.6 km       | PG         | 111.998        | 341.319        | -349.05 | 656.55   | 0.005     | fault           |
|                | NG         | 13.157         | 112.779        | 342.41  | /        | /         | normal          |
|                | PN         | 36.223         | 280.547        | 1.88   | 4284.04  | 0.020     | fault           |
| $F_1$           | PG         | 38.600         | 62.689         | -106.53 | 26.21    | 7.45e-4  | normal          |
|                | NG         | 10.984         | 14.376         | 104.54  | /        | /         | normal          |
|                | PN         | 29.85          | 46.67          | 2.05   | 19.17    | 6.18e-4  | normal          |
| $F_2$           | PG         | 30.382         | 53.809         | -80.81  | 0.022    | 4.82e-7  | normal          |
|                | NG         | 13.718         | 20.154         | 95.49   | /        | /         | normal          |
|                | PN         | 18.906         | 60.290         | -0.07  | 5.22     | 1.02e-4  | normal          |
The setting values of the four protections are 1766.2 kV/s, 0.1577 kA/s, 106.0 MW and 31.45 MW in order. Table 4 shows the simulation results when the positive pole at the end of the line is grounded through transition resistors of different sizes. It can be seen from the table that the time-domain-based protection has a limited ability to withstand the transition resistance. When the transition is higher than 200 Ω, protections may refuse to operate. Frequency domain protections based on wavelet transform and S transform have high resistance to transition resistance, and the resistance to transition resistance of the protection proposed in this paper can even reach more than 800 Ω.

### Noise

Although frequency domain protections have high resistance to transition resistance, they are susceptible to noise interference. Table 5 shows the simulation results of different protection schemes under different signal-to-noise ratios.

It can be seen from Table 5 that the calculated values of the four protection schemes far exceed their thresholds, so an additional noise identification method is very necessary. At present, the processing methods for noise mostly use the characteristic that the mean value of noise is 0 [22], so as to eliminate the influence of noise interference by means of summation or integration. But this method is extremely susceptible to mutation points. Figure 18 is a waveform diagram of the voltage at the measuring point in normal operation after superimposing noise with a signal-to-noise ratio of 15 dB. Figure 19 shows the sum of the voltage changes obtained in a 1 ms time window, and 100 tests have been performed. It can be seen that the average value of the voltage change is far greater than 0 for many times, which can easily cause protection malfunctions.

Figure 20 is the simulation result of 100 experiments using the method designed in this paper. It can be seen from the figure that the λs obtained each time is greater than the threshold, so that the noise interference can be accurately identified.
FIGURE 18  The voltage signal during normal operation superimposed with 15 signal-to-noise ratio noise

When the line fails, the measured fault signal may be doped with noise signals due to the influence of the measuring device. Figure 21 is the simulation result of the protection method in this paper after the fault signal is superimposed with the noise with a signal-to-noise ratio of 15 dB. It can be seen from these 100 experiments that the $\lambda_i$ obtained each time is less than $\lambda_{\text{set}}$. Therefore, even if the fault voltage contains noise signals, the protection can be effectively identified.

7.5  Time required for protection operation

We estimate the maximum operating time of the protection based on the fault at the end of the line. The traveling wave transmission speed is 300 km/ms and the total line length is 206.6 km. The data window is 1 ms before and after the failure. The number of multiplications required to perform S transformation on the data of 80 sampling points is:

$$M = 80^2 \log_2(80) + 80^2 \approx 46860 \ (33)$$

The protection in this paper does not require the entire matrix, and then count the number of multiplications required to find the power. The algorithm requires approximately $M \times 6/41 + 20 \times 6 \approx 6978$ multiplications in total. The DSP chip can complete a multiplication operation in one instruction cycle. At present, the instruction cycle of the TM320 series processor is below 20 ns, that is, the protection can complete the multiplication operation in $6978 \times 20 \times 10^{-6} \approx 0.14$ ms. Other action delays are shown in Table 6. It can be seen that the maximum action time of this protection scheme does not exceed 2 ms, and it has a certain quick action.

8  CONCLUSION

This paper analyses the frequency characteristics of the voltage at the measurement point under different fault conditions from the perspective of traveling waves, and constructs a protection judgment method and a noise identification method using high-frequency energy. The following conclusions are drawn through simulation analysis:
TABLE 6  Action delays

| Description                                           | Delay (ms) |
|-------------------------------------------------------|------------|
| The transmission time of traveling wave               | 0.7        |
| Data window length after failure                      | 1          |
| Photoelectric conversion and measurement delay        | 0.1        |
| S transformation and additional calculation           | 0.14       |
| Other calculation delays                               | 0.02       |
| Total time                                            | 1.96       |

ACKNOWLEDGMENT
This work was supported by the National Natural Science Foundation of China 51977144 and State Grid Corporation of China (KJ21-1-66).

1. Due to the existence of the current-limiting reactor, the high-frequency energy during the internal fault is greater than that during the external fault. The protection scheme based on high-frequency energy can accurately identify faults at different locations and different types of faults.

2. By comparing with other protection methods, the ability to withstand the transition resistance of the protection proposed in this paper can reach more than 800 Ω. The protection will not malfunction even in a noise environment with a 15 dB signal-to-noise ratio, and it can accurately identify the fault when the fault signal is superimposed with noise.

3. The protection can complete the fault identification within 2 ms, and only uses the single-ended information volume, without considering the problems of communication delay and data synchronization. This protection takes into account quick action and reliability at the same time.

4. The proposed protection also has shortcomings. We have not considered the error caused by the saturation of the capacitive voltage transformer. The lightning strike interference is greatly affected by the lightning strike position and the lightning strike form, and its frequency domain characteristics are more complicated, which is not considered in this article. In the future work, we will take more factors into consideration to improve existing protection schemes.

ORCID
Shimin Xue https://orcid.org/0000-0001-9441-0876
Shuo Chen https://orcid.org/0000-0001-8640-1005
Yabing Sun https://orcid.org/0000-0002-1276-1961
Cheng Gu https://orcid.org/0000-0002-6991-982X
Baiheng Liu https://orcid.org/0000-0003-1137-6284

REFERENCES
1. Alharbi, M., Isik, S., Bhattacharya, S.: Reliability comparison and evaluation of MMC based HVDC systems. In: 2018 IEEE Electronic Power Grid (eGrid), Charleston, South Carolina (2018)
2. Tang, L., et al.: Principle and implementation of ultra-high-speed travelling wave based protection for transmission line of flexible HVDC Grid. Power Syst. Technol. 42(10), 3176–3186 (2018)
3. Kong, F., Hao, Z., Zhang, B.: A novel travel-wave-based main protection scheme for S-Pnn $800$ KV UHVDC bipolar transmission lines. IEEE Trans. Power Delivery 31(5), 2159–2168 (2016)
4. Leterme, W., Beerten, J., Van Hertem, D.: Nonunit protection of HVDC grids with inductive DC cable termination. IEEE Trans. Power Delivery 31(2), 820–828 (2016)
5. Tang, L., et al.: A new differential protection of transmission line based on equivalent travelling wave. IEEE Trans. Power Delivery 32(3), 1359–1369 (2017)
6. Gao, S., et al.: A new relay protection principle of MMC-HVDC transmission lines. Power Syst. Prot. Control 46(13), 13–20 (2018)
7. Wu, J., et al.: An improved travel-wave protection scheme for LCC-HVDC transmission lines. IEEE Trans. Power Delivery 32(1), 106–116 (2017)
8. Xue, S., et al.: Longitudinal travelling wave differential protection for flexible HVDC system based on Marli model. Proc. Chin. Soc. Electr. Eng. 39(21), 6288–6300 (2019)
9. Wei, D., et al.: A fault identification method for HVDC transmission with long line based on boundary characteristics. Power Syst. Prot. Control 46(17), 75–82 (2018)
10. Yeap, Y.M., et al.: Time- and frequency-domain fault detection in a VSC-interfaced experimental DC test system. IEEE Trans. Ind. Inf. 14(10), 4353–4364 (2018)
11. Sneath, J., Rajapakse, A.D.: Fault detection and interruption in an earthed HVDC grid using ROCOV and hybrid DC breakers. IEEE Trans. Power Delivery 31(3), 973–981 (2016)
12. Yang, S., et al.: A fault protection scheme based on the difference of current-limiting reactor voltage for overhead mme based DC grids. Proc. Chin. Soc. Electr. Eng. 40(4), 1196–1211 (2020)
13. Xiang, W., 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)
14. Li, B., et al.: Single-ended protection scheme based on boundary characteristic for the multi-terminal VSC-based DC distribution system. Proc. Chin. Soc. Electr. Eng. 36(21), 5741–5749 (2016)
15. Mehrabikooshki, M., et al.: Single-End Protection Scheme for Lcc-Hvdc Transmission Lines Based on High Frequency Components of Transmission Line Current. In: 14th International Conference on Protection & Automation in Power System, Tehran (2020)
16. Stockwell, R.G., Mansinha, L., Lowe, R.P.: Localization of the complex spectrum: The S transform. IEEE Trans. Signal Process. 44(4), 998–1001 (1996)
17. Zhang, C., Song, G., Wang, T.: Analysis of traveling wave front and its application in fault location. In: 8th Renewable Power Generation Conference (RPG 2019), Shanghai (2019)
18. Dufour, C., et al.: Real-time simulation of power transmission lines using marli model with optimal fitting on dual-DSP card. IEEE Trans. Power Delivery 11(3), 412–419 (1996)
19. Howard, R.M.: White Noise: A Time Domain Basis. In: 2015 International Conference on Noise and Fluctuations (ICNF), Xi’an, China (2015)
20. Cohen, L.: Generalization of the Wiener-Khinchin theorem. IEEE Signal Process. Lett. 5(11), 292–294 (1998)
21. Wang, L., et al.: Pulsar signal detection based on S-transform. Acta Phys. Sinica 62(13), (2013)
22. Yang, S., Xiang, W., Wen, J.: Review of DC fault protection methods for the MMC based DC grid. Proceedings of the CSEE, Rome, Italy (2019)

How to cite this article: Xue, S., et al.: Research on the protection scheme of MMC-MTDC based on high frequency energy. IET Gener. Transm. Distrib. 1–12 (2021). https://doi.org/10.1049/gtd2.12201