Line Pilot Protection of Flexible DC Grid Based on Traveling-Wave JS Divergence

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ABSTRACT The proportion of renewable energy mainly including hydropower, photovoltaic and wind power is growing rapidly. DC transmission technology has become the main tool of new energy transmission. The protection scheme of the voltage source converter-based high voltage DC (VSC-HVDC) power grid is the prerequisite for the DC system. But, problems such as high resistance faults, distributed capacitance, and noise interference reduce the reliability of existing protection schemes. To solve the problem of resistance and noise interference in existing protection schemes, a double-ended protection scheme based on traveling wave JS divergence is proposed. First, the flexible HVDC transmission system is analyzed, according to which the expression of traveling wave power is derived, and its fault characteristics are summarized. Subsequently, a combined algorithm of the JS divergence based on the energy of the S-transform was proposed, and the modified algorithm was used to express the fault characteristics of traveling wave power. Finally, a flexible DC transmission system model is built. The performance of the scheme is verified by setting different interference factors (resistance, noise, distributed capacitance, synchronization error).

INDEX TERMS Renewable energy, DC converter, protection scheme, distributed capacitance, JS divergence.

I. INTRODUCTION Flexible DC transmission technology, especially flexible DC grid, is considered to be one of the effective technical means to solve the problem of renewable energy consumption in different regions. It also has broad application prospects in the fields of new energy grid connection, large-capacity long-distance power transmission, and new urban DC distribution networks [1], [2]. However, due to the low damping and inertia of flexible DC grids, DC faults will propagate extremely fast, causing severe damage to the entire HVDC grid within a few milliseconds [3]. Therefore, it is necessary to study the selective line protection that can quickly identify faults in DC grids.

There have been some studies on the protection principle of VSC-MTDC transmission lines. References [4] and [5] draws on the AC line protection scheme and uses current differential for fault identification. However, it is difficult to identify high resistance faults as a disadvantage [6]. Reference [7] proposes ultra-high-speed differential protection. But the existence of distributed capacitance makes it difficult to operate reliably within 3ms. Nowadays, the project adopts traveling wave protection as the main protection scheme for DC lines [8]. A scheme based on polarity is proposed in reference [9], but it requires two ends to communicate and has poor anti-interference ability. Reference [10] proposes a protection scheme based on voltage differentiation. However, it is still difficult to solve the problems of high resistance faults and noise interference. When scholars introduced wavelet transform into line protection, the frequency domain protection scheme developed vigorously [11]. Reference [12] proposed the principle of VSC-MTDC distribution network protection based on the frequency characteristics of differential current. However, whether this principle applies to VSC-MTDC needs to be discussed. Reference [13] proposes a scheme on the frequency characteristics of transient voltage. However, the protection schemes based on wavelet transform have the disadvantages of complicated principles, large calculation
the transmission of electrical characteristics is mainly used for fault identification by transmitting information such as voltage and current [20]. For example, a protection scheme that transmits transient energy and then judges the polarity of its difference, this type of scheme has high communication requirements. The protection scheme based on logic signals mainly identifies faults by transmitting judgment results (logic signals), such as identifying fault areas according to wavelet transform coefficients. This protection scheme requires less synchronization of the transmission channel [21].

So, the main protection scheme of VSC-MTDC has the following problems to be solved: 1) The traditional traveling wave protection scheme has poor sensitivity and has a protection dead zone. 2) It is difficult to distinguish between the DC side fault and the AC side fault. 3) The existing frequency domain analysis protection principle mostly uses single frequency band information, which leads to insufficient reliability. 4) The existing double-ended solution has the problem of long time delay, which is not conducive to the safety of the DC system.

Aiming at the above problems, a pilot protection scheme based on traveling wave JS divergence was proposed. Firstly, the traveling wave power expression of the flexible DC system is analyzed, and the difference between its internal fault and the external fault is found. Then, a combined algorithm that fuses S-transform energy and JS divergence is proposed and used to express fault features. The innovations are: 1) This paper analyzes the traveling wave power expression of the flexible DC system and finds its fault characteristics. 2) This paper proposes a new combination algorithm, which can effectively express the fault characteristics of traveling wave power. 3) The proposed scheme solves the problem of the long delay of traditional current differential protection. 4) Compared with the existing protection schemes, the proposed scheme has the better anti-interference ability.

In addition, Section II introduces the model of the flexible HVDC transmission system, and then analyzes the expression of traveling wave power and its fault characteristics. A combined algorithm that fuses S-transform energy and JS divergence is proposed in Section III. Section IV describes the detailed flow based on traveling-wave power JS divergence. Finally, the validity and superiority of the scheme are verified by the flexible HVDC model simulation. Simulation results are presented in Section V, and conclusions are provided in Section VI.

II. ANALYSIS OF FAULT CHARACTERISTICS
A. MODEL

The topology of the flexible DC system is shown in Figure 1 (Appendix). The faulty components of the system mainly include converters and transmission lines. The system topology adopts a symmetrical bipolar structure, the converter adopts a Modular Multilevel Converter (MMC) structure, and the transmission line adopts an overhead line. \(L_1\) and \(L_2\) represent current-limiting reactors, which the main function is to reduce the fault current rising rate. M and N in Fig. 1 are...
the measuring points of the protection device, which are responsible for collecting and processing fault information. F1, F2, and F3 represent reverse external, forward internal, and forward external faults, respectively. Since the half-bridge sub-module converters used in this system cannot clear faults, DC circuit breakers are arranged on both sides of the line. The fault current of the DC system has a large rising rate, and the protection scheme after a line fault needs to remove the fault within 6ms. Since the DC circuit breaker itself requires a breaking time of 3ms, the action time of the protection scheme is compressed to 3ms. Even the protection scheme based on double-ended electrical quantity must act within 10ms−20ms. However, the existing backup protection needs an action time of 1100ms due to the influence of the distributed capacitance, which is unacceptable for the DC converter [6]. Therefore, this paper proposes a novel double-ended protection scheme to solve this problem.

![FIGURE 1. VSC-HVDC grid test system.](image1)

![FIGURE 2. Schematic diagram of internal fault traveling waves.](image2)

### B. INTERNAL FAULT

Taking the F2 fault of the line as an example, the traveling wave will travel from F2 to the measurement points M and N. Among them, the backward traveling waves at the measurement point M are \(i_{Mf}\) and \(u_{Mb}\), and the forward traveling waves are \(i_{Mf}\) and \(u_{MF}\). The backward traveling waves at N are \(i_{Nb}\) and \(u_{Nb}\), and the forward traveling waves are \(i_{NF}\) and \(u_{NF}\). Since the traveling wave consists of the forward traveling wave and the reverse traveling wave, the calculation formula of the traveling wave voltage and traveling wave current at M is:

\[
\begin{align*}
    u_{M} & = u_{MF} + u_{Mb} \\
    i_{N} & = i_{MF} + i_{Mb}
\end{align*}
\]

After an internal fault, there are forward and backward waves in the line. If the specified positive direction is from the bus to the line, the opposite to the specified direction is the reverse traveling wave, and the same as the specified direction is the forward traveling wave. The transmission process is shown in Figure 2, where \(U_F\) is the fault voltage source.

Consider that the measurement points M and N are connected to the same current-limiting reactor and converter, take the measurement point on one side as an example for analysis. Define the product of traveling wave voltage and traveling wave current at M as traveling wave power, then the traveling wave power expression at M is [4]:

\[
\begin{align*}
    P_M & = (u_{MF} + u_{Mb})(i_{MF} + i_{Mb}) \\
    P_N & = (u_{NF} + u_{Nb})(i_{NF} + i_{Nb})
\end{align*}
\]

where \(P_M\) and \(P_N\) are the traveling wave power at the measurement point M and the measurement point N, respectively. Considering the relationship between refraction and reflection of a traveling wave signal, the following formula can be obtained [10]:

\[
\begin{align*}
    u_{M} & = (1 + \rho) \cdot B \cdot U_f \\
    i_{N} & = (1 - \rho) \cdot B \cdot I_f
\end{align*}
\]

where \(\rho\) represents the reflection coefficient; \(B\) represents the attenuation coefficient, which is determined by the wire; \(U_f\) and \(I_f\) represent the fault point voltage and current, respectively. Therefore, the calculation formula of the traveling wave power at the measurement point M can be expressed as:

\[
P_M = (1 + \rho)(1 - \rho) \cdot B^2 \cdot U_f \cdot I_f
\]

Since the system shown in Figure 1 is equipped with current limiting reactors on both sides of the line, it is an inductive element. The time domain expression of the reflection coefficient is [9]:

\[
\rho = 2e^{-(t - t_0)/\tau} - 1
\]

where \(t_0\) represents the moment when the fault traveling wave arrives at the measurement point; \(Z_c\) is impedance. It can be seen that the reflection coefficient of the current-limiting reactor gradually decreases from 1, which means that total
reflection occurs at time $t_0$. Bringing the reflection coefficient into formula (4), the traveling wave power is expressed as:

$$
\begin{align*}
P_M &= 2e^{-(t-t_0)/(L/2Z_C)}(2 - 2e^{-(t-t_0)/(L/2Z_C)}) \cdot B^2 \cdot U_t \cdot I_t \\
P_N &= 2e^{-(t-t_0)/(L/2Z_C)}(2 - 2e^{-(t-t_0)/(L/2Z_C)}) \cdot B^2 \cdot U_t \cdot I_t
\end{align*}
$$

(6)

Because the current-limiting reactors at measurement point M and the measurement point N are the same, and the fault voltage source is the same. Therefore, the traveling wave power expressions at M and N are consistent. In addition, the traveling wave power is zero at time $t_0$, and its value is the smallest. When the fault time increases from $t_0$, the traveling wave power gradually increases, and the changing trend of the $P$ on M and N is almost the same. To sum up, when the line loss is ignored, the traveling wave power is almost the same when the internal fault occurs.

C. EXTERNAL FAULT

Taking the $F_1$ fault as an example, the schematic diagram of when an external fault occurs is shown in Figure 3. The forward traveling wave reaches the measuring point N from $F_1$ through M and the transmission line, and then the traveling wave is reflected back to the measuring point M. The traveling waves at M are the forward traveling waves $i_{Mf}$ and $u_{Mf}$, the reverse traveling waves at N are $i_{Nf}$ and $u_{Nf}$, and the forward traveling waves are $i_{NF}$ and $u_{NF}$. Obviously, the fault information obtained by the measurement points on both sides is different when there is an external fault.

At this time, the traveling wave power expressions at measurement points M and N are:

$$
\begin{align*}
P_M &= I_f^2 Z_C \\
P_N &= 2e^{-(t-t_0)/(L/2Z_C)}(2 - 2e^{-(t-t_0)/(L/2Z_C)}) \cdot B^2 \cdot U_t \cdot I_t
\end{align*}
$$

(7)

When $F_3$ faults, the traveling wave arrives at the measuring point M from the fault point through the measuring point N and the transmission line, and then reflected to N. The traveling wave felt at the measuring point N is the forward traveling wave, and the reverse traveling wave and the forward traveling wave are felt at the measuring point M. At this time, the traveling wave power expression of measurement points M and N is:

$$
\begin{align*}
P_M &= 2e^{-(t-t_0)/(L/2Z_C)}(2 - 2e^{-(t-t_0)/(L/2Z_C)}) \cdot B^2 \cdot U_t \cdot I_t \\
P_N &= I_f^2 Z_C
\end{align*}
$$

(8)

Equations (7) and Equation (8) show that when there is an external fault, the expressions of the traveling wave power on M and N are completely different. Since the wave impedance of the transmission line is a constant value, it is generally (200~400)$\Omega$. Therefore, the traveling wave power at the near-end measurement point hardly changes in external fault. At this time, there is a huge difference between the power of the far end and the characteristics of the near end.

To sum up, the following conclusions can be drawn from the derivation of the traveling wave power expression:

1) Internal faults: the traveling wave powers on both sides are almost the same, and the trend of change is the same;
2) External faults: the traveling wave powers on both sides are very different, and one side is very different. One side is almost constant over time.
function, frequency, and imaginary unit, respectively. It can introduce the concept of S-transform energy to solve this problem. Assuming that the signal is then its S-transform form is:

\[
E = \sum_{kT} |S_n(KT, x(t))|^2 \tag{14}
\]

where \(E\) represents the energy of a single frequency of the \(x(t)\) signal. Combining equations (13) and (14), the energy \((E_i)\) of the sampled signal at different frequencies can be obtained as:

\[
E_i = |S_i|^2 + |S_{i2}|^2 + \cdots + |S_{iN}|^2 \quad i = 1, 2, \ldots, N/2 \tag{15}
\]

According to this, the total energy of the signal in the entire frequency domain can be obtained as:

\[
E = E_1 + E_2 + \cdots + E_{N/2} \tag{16}
\]

Then the ratio of the signal energy of different frequencies to the total energy is:

\[
p_i = \frac{E_i}{E} \tag{17}
\]

where \(p_i\) represents the energy ratio of the frequency signal. Define the energy proportion of the traveling wave power on both sides as \(p_{ix}\) and \(p_{iy}\) respectively, then the expression of the energy JS divergence of the traveling wave power on both sides is:

\[
D_{JS}(P_{ix}, P_{iy}) = \frac{\sigma_i^2 + \sigma_y^2 + 1/2(\mu_x - \mu_y)^2}{4\sigma_M^2} + \frac{1}{4} \log \frac{\sigma_M^4}{\sigma_i^4 + \sigma_y^4} - \frac{1}{2} \tag{18}
\]

where \(\sigma_i^2, \sigma_y^2, \mu_x, \mu_y\) and are calculated by \(p_{ix}\) and \(p_{iy}\), respectively.

To sum up, the calculation steps of traveling wave power energy JS divergence are as follows:

1. S-transform the sampled signal to get its matrix form:

\[
S = \begin{bmatrix}
f_1 & S_{11} & S_{12} & S_{1N} \\
f_2 & S_{21} & S_{22} & S_{2N} \\
\vdots & \vdots & \vdots & \vdots \\
S_{2N} & S_{N1} & S_{N2} & S_{NN}
\end{bmatrix} \tag{13}
\]

where \(S_{ij}\) represents the amplitude and phase of the signal at the corresponding frequency and time. In addition, since the energy calculation formula of the S transform is:

\[
E = \sum_{kT} |S_n(KT, x(t))|^2 \tag{14}
\]

where \(E\) is the sampling point; \(T\) is the time interval; \(S_n(KT, x(t))\) represents the value of the frequency corresponding to \(x(t)\).

\[
N \quad \text{is that it has symmetry, which meets the needs of this paper.}
\]

\[
\mu_n = \frac{1}{2} (\mu_1 + \mu_2)
\]

\[
\sigma_n^2 = \frac{1}{2} (\sigma_1^2 + \sigma_2^2)
\]

where \(\mu_1, \mu_2, \mu_n\) represent the expected value; \(\sigma_1^2, \sigma_2^2, \sigma_n^2\), represent the variance.

Then the calculation formula of JS divergence DJS is:

\[
D_{JS}(F, P) = \frac{\sigma_1^2 + \sigma_2^2 + 1/2(\mu_1 - \mu_2)^2}{4\sigma_M^2} + \frac{1}{4} \log \frac{\sigma_M^4}{\sigma_1^4 + \sigma_2^4} - \frac{1}{2} \tag{10}
\]

The above formula shows the distribution of the data required to calculate the JS divergence. Therefore, this paper introduces the concept of S-transform energy to solve this problem. Assuming that the signal is \(x(t)\), its S transform formula is as follows:

\[
S(T, x) = \int_{-\infty}^{\infty} x(t)w(\tau - t) \exp(-2\pi j\tau f)dt \tag{11}
\]

where \(w(\tau - t), f, j\) represent the Gaussian window function, frequency, and imaginary unit, respectively. It can be seen that the S-transform has better time-frequency resolution. Let \(x[KT]\) be the discrete time series of the signal \(x(t)\), then its S-transform form is:

\[
S[KT, x] = \sum_{m=0}^{N-1} X[k] e^{-2\pi jmk} e^{2\pi jmk}, \quad n \neq 0 \tag{12}
\]
and the JS divergence is the smallest at this time. When an external fault occurs, the traveling wave powers of M and N are completely different, and the JS divergence is the largest at this time. Therefore, the JS divergence fault characteristics of the flexible DC system are summarized in TABLE 1.

**TABLE 1. Characteristics of JS divergence of traveling wave power.**

| Condition | M terminal | N terminal | JS divergence |
|-----------|-----------|-----------|---------------|
| F₁        | constant  | increase  | 1             |
| F₂        | increase  | increase  | 0             |
| F₁        | increase  | constant  | 1             |

**IV. SCHEME**

**A. STARTUP ELEMENT**

In this paper, the criterion of starting components is constructed by current differentiation. When the current differential \( \left| \frac{di}{dt} \right| \) is greater than the threshold \( k_{set} \)

\[
\left| \frac{di}{dt} \right| > k_{set} \tag{19}
\]

where \( i \) represents the pole current; \( k_{set} \) represents the threshold, and its value is related to the system parameters. After a fault occurs, the rapid increase of the fault current causes its differential to increase rapidly. In order to ensure reliability, the protection scheme can be entered only after two consecutive start-up element actions are set. Assuming that the frequency used is 20kHz, the action time of the starting element is 0.15ms, and its quickness is good.

**B. FAULT IDENTIFICATION ELEMENT**

According to the previous analysis, the following conclusions can be drawn: 1) In the case of an intra-area fault, the traveling wave power on both sides is the same, and its JS divergence is theoretically 0. 2) In an out-of-area fault, the traveling wave powers of M and N are completely inconsistent, and the JS divergence is theoretically 1. However, there are noises, measurement errors, synchronization errors, and other disturbances in practical engineering. The calculated JS divergence cannot fully reflect the correlation of the traveling wave power on both sides. Therefore, this paper sets the threshold to 0.5, which can be adjusted according to different projects. In summary, the criteria for identifying elements of the protection scheme are:

\[
\begin{align*}
\text{internal : } D_{JS} & \leq 0.5 \\
\text{external : } D_{JS} & > 0.5
\end{align*} \tag{20}
\]

where \( D_{JS} \) represents the JS divergence of the traveling wave power on both sides. When the JS divergence is lower than the threshold, it is judged as an internal fault; when it is higher than the threshold, it is judged as an external fault.

**V. SIMULATION**

**A. INTERNAL FAULT**

Take the internal fault \( F₂ \) as an example to verify the correctness of the internal fault of the scheme. The previous analysis shows that the traveling wave power on both sides is almost the same after an internal fault occurs, and its JS divergence is theoretically 0. The internal midpoint fault is set, and the JS divergence of the traveling wave power on both sides is calculated. The simulation results are shown in Figure 5.

Figures 5(a) and (b) represent the traveling wave power at measurement points M and N respectively, and the waveforms are almost the same. This is because the fault location is set at the midpoint, and information such as current and voltage are obtained on both sides. Figure 5(c) is obtained by calculating the S-transform energy for the traveling wave power in (a) and (b), and then calculating the JS divergence. Observing Figure 5(c), it can be seen that the JS divergence is almost zero at this time, which means that the traveling wave powers on both sides are the same. The simulation...
results satisfy the theoretical analysis above, and the protection scheme can accurately determine the internal fault at this time.

B. EXTERNAL FAULT
Considering the symmetry of the DC system shown in Figure 1, the correctness of the scheme is analyzed by taking an external fault on one side as an example. The previous analysis shows that after an external fault, the traveling wave power at N is almost unchanged for some time; the traveling wave power at M changes with time; the JS divergence of the traveling wave power on both sides is theoretically 1. Set the forward external fault F3, and calculate the traveling wave power and JS divergence as shown in Figure 6.

C. POLE-TO-GROUND FAULT
The condition of the single-pole ground fault is also simulated in this paper. Set F1, F2, F3 faults respectively, and the simulation results are shown in Table 2. When an internal fault occurs, the traveling wave power on both sides is almost the same, and the measured JS divergence is almost 0. At this time, the JS divergence is higher than the threshold value, which meets the fault identification component. However, when an external fault occurs, the traveling wave power near the fault point is almost unchanged, and the traveling wave power at the far fault point tends to increase. At this point, the JS divergence is almost 1.

| Fault type | Pm(kW) | Pn(kW) | DRS |
|------------|--------|--------|-----|
| F1         | 1025   | 1579-2187 | 0.954 |
| Positive   | F2     | 2108-3575 | 2108-3575 | 0.008 |
| F3         | 1927-3097 | 988     | 0.971 |
| F1         | 975    | 1354-3674 | 0.992 |
| Negative   | F2     | 1983-3371 | 1981-3369 | 0.014 |
| F3         | 1008-2587 | 754     | 0.987 |

D. FAULT RESISTANCE AND FAULT DISTANCE
The ability to withstand fault resistance and fault distance is an important indicator for judging the performance of the protection scheme. The eigenvalues of traveling wave power in the scheme proposed in this paper are affected by fault resistance, but the JS divergence is only affected by the correlation. In view of the symmetry of the flexible DC system and the unity of the fault source, the traveling wave power on both sides is uniformly affected by the fault resistance. That is, when affected by the fault resistance at the same time, the correlation of the traveling wave power on both sides is not changed. Therefore, the scheme is not affected by fault resistance in theory.

In order to identify the reliability of the scheme, different fault distances and fault resistances were simulated and their JS divergences were calculated. Since the total length of the line is 220km, the reverse external fault F1 is set to -50km, the internal fault F2 is 10km~200km, and the forward external fault F3 is 250km. Obviously, the JS divergence is higher than the threshold of 0.5 when the external fault occurs, and the JS divergence is lower than the threshold of 0.5 when the internal fault occurs.

To verify the superiority of the proposed protection principle in withstanding transitions, several commonly used single-ended protection principles were introduced and compared with the proposed protection principles. The comparison results are shown in Table 3. Traveling wave protection, as a common protection scheme in engineering, can only withstand 100Ω. The protection scheme of reference [12] can identify a fault resistance of up to 500Ω, while the proposed protection scheme can withstand 700Ω.

| Fault resistance | 100Ω | 200Ω | 400Ω | 600Ω |
|------------------|------|------|------|------|
| proposed protection | ✓    | ✓    | ✓    | ✓    |
| DC reactor voltage amplitude protection [7] | ✓ | ✓ | × | × |
| Frequency domain protection of DC reactor [12] | ✓ | ✓ | ✓ | × |

E. NOISE
The scheme uses the traveling wave signal to calculate the JS divergence, and the traveling wave signal is the eigenvalue considering the distributed capacitance. Therefore, this scheme is naturally not affected by distributed capacitance, and a large number of literature have verified this feature [10], [11], [12], [13], [14], [15], and will not be repeated in this article.
Correspondingly, traveling wave signals also have disadvantages, such as being susceptible to high-frequency noise. The problem of noise interference needs to be solved because it may affect the reliability of the protection scheme [14]. The signal-to-noise ratio (SNR) is commonly used to express the intensity of noise interference. The larger the signal-to-noise ratio, the weaker the noise interference. The noise in this paper includes background noise, impulse noise, synchronous and asynchronous noise, etc. The above-mentioned noise is generally considered to be Gaussian-distributed white noise [16]. The amplitude distribution of Gaussian white noise obeys the Gaussian distribution, and its power spectral density is evenly distributed. Equation (21) is the calculation formula of the probability distribution function. Where \( \mu_1 \) stands for mathematical expectation, and \( \sigma_1 \) stands for current variance of the Gaussian distribution.

\[
P_1(x) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{\left(-\frac{(x-\mu_1)^2}{2\sigma_1^2}\right)}  \tag{21}
\]

In order to verify the noise tolerance of the scheme, different signal-to-noise ratios are added to the traveling wave power. The simulation results are shown in Table 4. The JS divergence obtained by the 10dB signal-to-noise ratio is less than the JS divergence of 40dB, which means that the noise affects the judgment of the scheme. Therefore, the scheme can work under high noise interference.

### TABLE 4. Simulation results for different noises.

| Fault | SNR | \( P(kW) \) | \( D_3 \) | Result |
|-------|-----|-------------|---------|--------|
|       |     | M          | N       |        |
| \( F_1 \) | 40dB | 785 | 3158 | 0.997 | √ |
| \( F_1 \) | 10dB | 746 | 3078 | 0.975 | √ |
| \( F_2 \) | 40dB | 3015 | 2996 | 0.130 | √ |
| \( F_2 \) | 10dB | 2998 | 2972 | 0.354 | √ |
| \( F_3 \) | 40dB | 3521 | 536 | 0.989 | √ |
| \( F_3 \) | 10dB | 3412 | 511 | 0.965 | √ |

The anti-noise interference capabilities of different protection schemes are compared, and the results are shown in Table 5. As shown in Table 5, in addition to traveling wave protection, the other two DC reactor-based protection schemes can withstand 20dB noise interference. Obviously, the proposed protection scheme is more resistant to noise interference.

### F. SYNCHRONIZATION ERROR AND RUNTIME

The traditional scheme adopts the principle of longitudinal differential to realize fault identification. The longitudinal differential principle utilizes a few milliseconds of data to determine the fault area. However, the flexible DC system has the characteristics of large fault current and high rise rate. Small synchronization errors can cause the protection principle to fail. Therefore, the double-ended protection principle should focus on the influence of synchronization errors. The scheme described in this paper uses the full waveform signal of the traveling wave power on both sides to determine the fault area. Small synchronization errors will not change the overall waveform change, that is, the JS divergence is less affected. Therefore, it is theoretically tolerant to synchronization errors.

In order to ensure the reliability of the scheme, this paper sets a variety of synchronization errors and calculates the JS divergence on both sides. The test results are shown in Table 6. When the synchronization error is less than 0.15ms, although there is a difference in the traveling wave power on both sides, the JS divergence is still less than the threshold, and the protection scheme can still identify the fault. However, when the synchronization error reaches 0.2ms, the JS divergence of the traveling wave power is higher than the threshold, and the protection scheme fails at this time. Therefore, this scheme can accept a synchronization error of 0.15ms. Compared with the existing scheme’s 0.1ms tolerance to synchronization error, this scheme has achieved a large performance improvement.

### TABLE 5. Ability to withstand noise interference with different protection principles.

| SNR | 10dB | 20dB | 30dB | 40dB |
|-----|------|------|------|------|
| **proposed protection** | ✓ | ✓ | ✓ | ✓ |
| DC reactor voltage amplitude protection [7] | × | ✓ | ✓ | ✓ |
| Frequency domain protection of DC reactor [12] | × | ✓ | ✓ | ✓ |
| Traveling wave protection [11] | × | × | ✓ | ✓ |

### TABLE 6. Test results of synchronization error.

| Error | \( P(kW) \) | \( D_3 \) | Result |
|-------|-------------|---------|--------|
|      | M          | N       |        |
| 0.05ms | 2972 | 2963 | 0.009 | √ |
| 0.10ms | 2960 | 2899 | 0.013 | √ |
| 0.15ms | 2951 | 2728 | 0.270 | √ |
| 0.20ms | 2911 | 169 | 0.954 | × |
In addition, the simulation results of the operating time of different protection principles are listed in Table 7. Since reference [7] uses the principle of current differential structure protection, the protection will act when $di/dt$ exceeds the threshold. Therefore, the protection principle of [7] has the least operating time. The protection principle represented by reference [7] is simple to apply, but its reliability is weak.

The operating time of the proposed protection principle, reference [11] and reference [12] are both within 11ms. But, the proposed protection principle has stronger anti-interference performance and is more suitable for VSC-MTDC systems. Obviously, only the proposed protection scheme can have an action time of less than 3ms under a fault of 10dB+600Ω.

### TABLE 7. Comparison results of the action time of different protection principles.

| SNR   | Proposed protection | References [7] | References [12] | References [11] |
|-------|---------------------|----------------|-----------------|-----------------|
| 10dB+600Ω | 4.635ms           | 3.21ms          | 9.95ms          | 10.5ms          |
| 20dB+200Ω | 4.572ms           |                | 9.91ms          |                 |
| 20dB+500Ω | 4.631ms           |                |                |                 |
| 30dB+500Ω | 4.55ms            |                |                |                 |

### VI. CONCLUSION

To solve the problems of distributed capacitance and synchronization error, a protection scheme based on JS divergence of traveling wave power is proposed. The main work and contributions of this paper are as follows:

1. The traveling wave power expression of the flexible DC transmission system is derived for the first time. The fault characteristics of the DC system are clarified, that is, the traveling wave power is completely the same when the internal fault occurs, and the difference is very large when the external fault occurs.
2. The combined algorithm of JS divergence and $S$ transform energy is proposed for the first time. The algorithm can clearly express the difference of traveling wave power, that is, JS divergence is 0 for internal faults and 1 for external faults.
3. Compared with the existing scheme, this scheme is not affected by distributed capacitance and is more resistant to noise, fault resistance, and synchronization error.

### APPENDIX

The parameters of the VSC-HVDC system are listed in Table 8 and Table 9.

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