

Initial Traveling-wave-based Single-ended Setting-less Protection for VSC-MTDC Grids

Meng Li, *Member, IEEE*, Jiaying Ning, *Student Member, IEEE*, Jinghan He, *Fellow, IEEE*,
Sohrab Mirsaedi, *Senior Member, IEEE*, and Ming Nie, *Student Member, IEEE*

Abstract—The main challenges associated with the existing protection schemes are that they are easily affected by the transition resistance and require threshold settings. To address such challenges, this paper proposes a single-ended setting-less protection scheme for VSC-MTDC grids which is based on waveform characteristics of initial traveling waves (ITWs). In this paper, first, the amplitude and transmission characteristics of the ITW are deduced, and then the characteristic that transition resistance only affects the amplitude of the ITW but does not affect its waveform is revealed. Subsequently, the difference between the ITWs in internal and external faults is investigated. Moreover, the time domain expressions of the ITW are obtained when faults occur on both sides of current-limiting reactor (CLR), respectively. Finally, an overall protection scheme is proposed which can distinguish between internal and external faults through comparing the similarity of ITW waveform. The salient feature of the proposed strategy is that it is not affected by the transition resistance, and has an adequate tolerance to the fault location, lightning disturbance, noise, etc. To verify the effectiveness and reliability of the proposed scheme, several simulations have been carried out on Zhangbei four-terminal VSC-HVDC grid using PSCAD/EMTDC software.

Index Terms—Current-limiting reactor, initial traveling wave, setting-less protection, transition resistance, VSC-MTDC.

I. INTRODUCTION

VOLTAGE source converter-based high voltage direct current (VSC-HVDC) technology has significant advantages in supplying power for passive systems and flexible interconnection of power grids, etc., owing to its low harmonic content and high controllability [1]–[3]. To improve the reliability and flexibility of power supply, the construction of voltage source converter-based multi-terminal high voltage direct current (VSC-MTDC) grids is an important direction for future application [4]. For example, ± 500 kV Zhangbei four-terminal VSC-HVDC grid has been completed and put into operation in China [5].

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M. Li, J. X. Ning (corresponding author, email: ningjx@bjtu.edu.cn), J. H. He, S. Mirsaedi, and M. Nie are with the School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China.

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When faults occur on the dc line of VSC-MTDC grids, the superposition of the outputs from multi-terminal converter stations will aggravate the harm caused by the overcurrent [6]–[8]. Moreover, the low damping characteristics of VSC-MTDC grids make the fault spread extremely fast, which may endanger the entire grid within a few ms [9]. Therefore, to avoid further expansion of the accident, faults must be isolated quickly and reliably, which necessitates major requirements for the protection scheme suitable for VSC-MTDC grids.

At present, protection schemes for VSC-MTDC grids can be divided into two main groups, i.e. double-ended information-based and single-ended information-based protections.

1) Double-ended protections: A directional pilot protection scheme is proposed in [10], which is based on the amplitude ratio of the voltage detail coefficients. The direction signal has low requirements on hardware, but the quickness of protection is affected by communication delay. In [11], the cross-wavelet transform is employed to identify internal and external faults. However, the quickness of protection still needs to be improved. In [12], a modulus power-based pilot protection scheme is proposed for detecting the fault location. However, data synchronization errors will be an inevitable factor, which makes the protection operation delayed. Therefore, the quickness of double-ended protection is a challenging issue that needs to be improved. For fast operation of protection, single-ended protection has been extensively studied.

2) Single-ended protections: Traveling wave information at the midpoint of lines is taken as the benchmark to discriminate between the internal fault and external fault in [13]. However, the benchmark is simulation-based and lacks theoretical support. Furthermore, the protection reliability depends on threshold setting. In [14], a protection scheme based on the distortion factor of the line-mode traveling wave is proposed. This scheme is independent of boundary components, but the transfer function is simulated by an approximate formula and the reliability of the threshold needs to be improved. An ultra-high-speed protection scheme adopting local information is proposed in [15], but this scheme does not consider the impact of lightning disturbance. In [16], the impact of lightning disturbance is considered, and a high-speed protection scheme is proposed. However, reliability of the scheme still depends on the threshold setting. Some scholars try to use waveform correlation-based methods to identify fault zones in [17]–[19], but such methods also rely on the threshold. In the above schemes, the threshold setting is a major problem in single-ended protection. The contradiction between reliability,

sensitivity, selectivity, and quickness of protection needs to be coordinated by adjusting the threshold. For example, the sensitivity of protection will be reduced inevitably while enlarging the threshold to improve reliability. Therefore, protection schemes depending on threshold setting cannot make the four characteristics of protection achieve their best at the same time. Once the threshold is improperly set, the protection performance will be seriously affected. There are already cases of protection maloperation caused by threshold-setting problems in projects, such as [20] and [21].

To resolve the challenge of threshold setting, some scholars put forward the idea of “setting-less” protection. In [22], model identification methods are applied to achieve setting-less protection. In [23], setting-less component protection is proposed by using distributed dynamic state estimation. However, the above methods will be affected by transition resistance. More precisely, when high transition resistance faults occur, the reliability of the protection will be threatened.

In summary, there are three key challenges to be solved in the existing protection schemes. First, the quickness of protection needs to be improved in VSC-MTDC grids. Second, setting-less protections independent of threshold setting are required for enhancing the protection performance. Third, it is also necessary to study the protection scheme not affected by the transition resistance.

To overcome the aforementioned challenges, a single-ended setting-less protection is proposed for VSC-MTDC grids, which is realized by comparing internal similarity and external similarity of initial traveling waves (ITWs) waveform to identify the internal and external faults. The main contributions of the proposed protection scheme are as follows:

1) The proposed scheme only needs to compare the internal similarity and the external similarity for achieving fault identification, and it does not need to set a threshold. Thus, the problem of protection maloperation caused by improper threshold setting is solved from the root.

2) Using the characteristic that transition resistance only affects the amplitude of the ITW but does not affect its waveform, normalization on the ITW can effectively eliminate the influence of transition resistance.

3) Considering the frequency-varying characteristics of the line distribution parameters, the transmission characteristics of the ITW through the line and current-limiting reactor (CLR) are analyzed. Time-domain expressions of the ITW are obtained, which can provide theoretical support for ITW analysis.

II. CHARACTERISTICS ANALYSIS OF ITW

A. Amplitude of ITW

Taking the fault on positive lines as an example for analysis, the fault component diagram is shown in Fig. 1. P and N represent the positive and negative poles, U_f is the memory voltage, R_f is the transition resistance. $U_{fp}(s)$ and $U_{fn}(s)$ are the positive pole-to-ground and negative pole-to-ground voltages at the fault point. $I_{fp}(s)$ and $I_{fn}(s)$ are the positive pole-to-ground and negative pole-to-ground currents at the fault points, respectively.

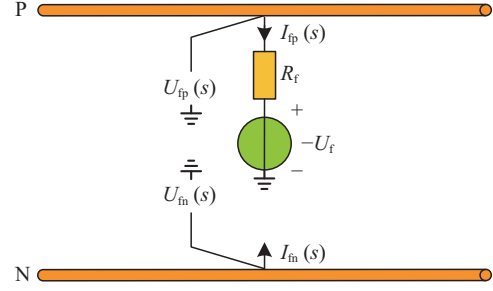


Fig. 1. The fault component diagram.

From Fig. 1, boundary conditions of the fault component can be obtained as:

$$\begin{cases} U_{fp}(s) = -U_f + I_{fp}(s)R_f \\ I_{fn}(s) = 0 \end{cases} \quad (1)$$

Due to the coupling effect of the electrical quantities between the positive and negative poles, it is necessary to decouple them to convert the electrical quantities from phase domain into mode domain [24]. The phase-to-mode transformation formula is expressed as:

$$\begin{bmatrix} x_1 \\ x_0 \end{bmatrix} = \frac{\sqrt{2}}{2} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_p \\ x_n \end{bmatrix} \quad (2)$$

where x_1 and x_0 are the line-mode and ground-mode quantities, respectively; and x_p and x_n are the positive-pole and negative-pole quantities, respectively.

After decoupling, the mode domain network at the fault point can be represented by:

$$\begin{cases} U_{f1}(s) = -I_{f1}(s)Z_{c1}(s) \\ U_{f0}(s) = -I_{f0}(s)Z_{c0}(s) \end{cases} \quad (3)$$

where $U_{f1}(s)$ and $U_{f0}(s)$ are line-mode and ground-mode voltages at the fault point; $I_{f1}(s)$ and $I_{f0}(s)$ are the line-mode and ground-mode currents at the fault point; $Z_{c1}(s)$ and $Z_{c0}(s)$ are line-mode and ground-mode wave impedances.

The expression of the ITW amplitude in the case of pole-to-ground faults can be obtained by combining (1), (2) and (3):

$$\begin{cases} U_{f1}(s) = -\frac{\sqrt{2}U_f Z_{c1}(s)}{Z_{c1}(s) + Z_{c0}(s) + 4R_f} \\ U_{f0}(s) = -\frac{\sqrt{2}U_f Z_{c0}(s)}{Z_{c1}(s) + Z_{c0}(s) + 4R_f} \end{cases} \quad (4)$$

In the same way, the amplitude of the ITW in the case of pole-to-pole faults can be obtained as:

$$\begin{cases} U_{f1}(s) = -\frac{\sqrt{2}U_f Z_{c1}(s)}{Z_{c1}(s) + R_f} \\ U_{f0}(s) = 0 \end{cases} \quad (5)$$

From (4) and (5), it is evident that the transition resistance only affects the amplitude of the ITW and does not affect its waveform shape regardless of the fault type. Therefore, to eliminate the influence of the transition resistance, the ITW can be normalized and processed into the ITW with

an amplitude of 1 for subsequent calculation. To verify the correctness of the above analysis, Fig. 2(a) shows the ITWs under different transition resistances, and Fig. 2(b) is the normalized ITWs.

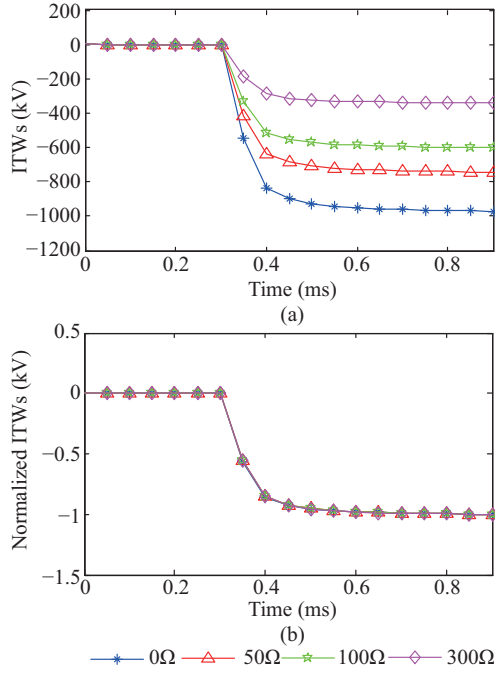


Fig. 2. ITWs under different transition resistances. (a) ITWs. (b) Normalized ITWs.

It can be seen amplitudes of the ITWs differs under different transition resistances. The larger the transition resistance, the smaller the amplitude. The normalized ITWs are identical, which verified the transition resistance does not affect the waveform shape of ITWs.

B. Transmission of ITW

The ITW will pass through the transmission line and the CLR during the transmission process. The influence of the two on ITW should be analyzed.

1) Attenuation and Distortion of ITW by Transmission Line

Marti model, which takes into account the frequency-varying characteristics of the line distribution parameters, is used to analyze the transmission characteristics of ITW. The frequency domain equivalent of Marti model is shown in Fig. 3.

In Fig. 3, M and N represent both ends of the line, $U_M(s)$ and $U_N(s)$ are the voltages at the ends of M and N, $I_M(s)$ and

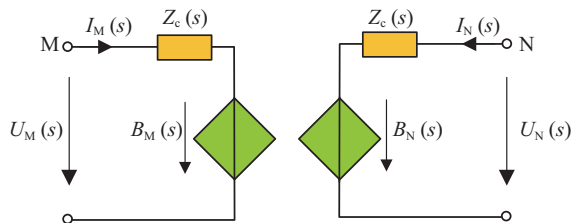


Fig. 3. The frequency domain equivalent of Marti model.

$I_N(s)$ are the currents at the ends of M and N, $Z_c(s)$ is the wave impedance, $B_M(s)$ and $B_N(s)$ are the backward traveling waves at the ends of M and N. If only the information at the local end is used, $B_M(s)$ and $B_N(s)$ can be calculated by:

$$\begin{cases} B_M(s) = U_M(s) - Z_c(s)I_M(s) \\ B_N(s) = U_N(s) - Z_c(s)I_N(s) \end{cases} \quad (6)$$

If only the information at the opposite end is used, $B_M(s)$ and $B_N(s)$ can be obtained by:

$$\begin{cases} B_M(s) = F_N(s)A(s) \\ B_N(s) = F_M(s)A(s) \end{cases} \quad (7)$$

where $F_M(s)$ and $F_N(s)$ are forward traveling waves at the ends of M and N; $A(s)$ is the transfer function.

The wave impedance and transfer function in Marti model can be expressed as:

$$\begin{cases} Z_c(s) = q_0 + \sum_{i=1}^k \frac{q_i}{s + p_i} \\ A(s) = e^{-s\tau} \sum_{i=1}^m \frac{q_i}{s + p_i} \end{cases} \quad (8)$$

where q_0 is the free term; q_i and p_i are the zeros and poles; k is the number of wave impedance zeros and poles; m is the number of transfer function zeros and poles; τ is the fastest transmission time of traveling wave on the whole transmission line, $\tau = l/v$; l is the distance from the fault point to the protection measurement point, and v is the maximum speed of the traveling wave.

From the above analysis, it can be seen that the time ITW arrives at the protection measurement point mainly depends on the fault location. The farther the fault point is, the longer the arrival time of the ITW is. The summation term in the transfer function represents the attenuation and distortion of the ITW. The attenuation has little effect on the ITW after normalization, so the distortion of the ITW is mainly concerned. Generally, the farther the fault point is, the more serious the distortion of the ITW is.

2) Refraction of ITW by CLR

In case of external faults, the ITW will be refracted when passing through the CLR. It is necessary to analyze the refraction effect on the ITW. Taking the bus side fault of the opposite-end CLR as an example, its Peterson equivalent diagram is shown in Fig. 4.

The forward traveling wave at point N after refraction by the CLR is:

$$F_N(s) = 2U_f(s) \frac{Z_c(s)}{Z_c(s) + sL} \quad (9)$$

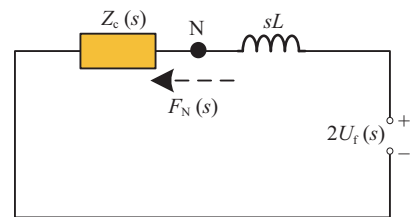


Fig. 4. Peterson equivalent diagram.

where $2U_f(s)$ is Peterson equivalent voltage source; L is the inductance value of CLR.

Having determined $F_N(s)$, the ITW reaching the local-end protection can be obtained by (7). It can be seen from (7) and (9) that the refraction of the CLR will further aggravate the distortion of the ITW, so ITW shapes on both sides of the CLR significantly change. It should be noted that the calculations in Section II-B are carried out in the mode domain, and finally converted into phase domain.

To verify the correctness of the theoretical analysis in Section II-B, the ITWs under different fault locations are simulated and normalized, as shown in Fig. 5(a). To compare the degree of distortion, they are further translated to the same starting point, as shown in Fig. 5(b). The total length of the line is 200 km.

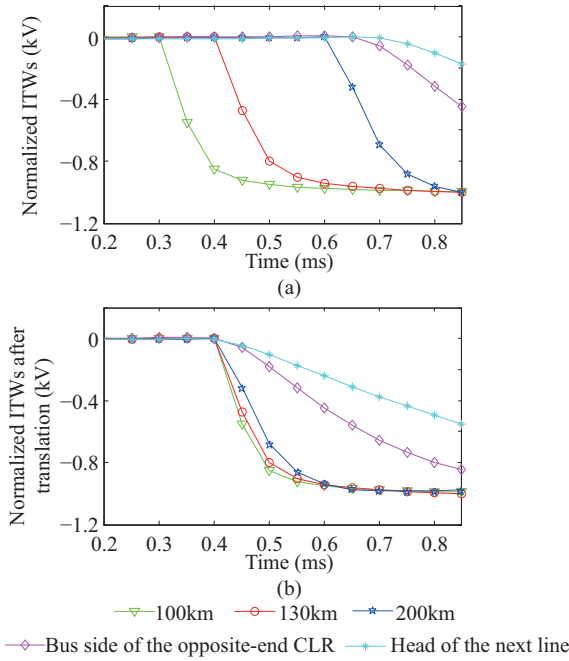


Fig. 5. ITWs under different fault locations. (a) Normalized ITWs. (b) Normalized ITWs after translation.

From Fig. 5(a), as the fault distance increases, the arrival time of the ITW also becomes longer. From Fig. 5(b), the farther the fault location is, the more serious the distortion of the ITW is. Furthermore, the ITW refracted by the CLR will produce more obvious distortion. For the fault on the head of the next line, the ITW at the local-end protection is obtained after the fault traveling wave is refracted by the CLR twice and transmitted by the line once. Therefore, its distortion is more serious compared with the bus side fault of the opposite-end CLR. The simulation results can verify the correctness of the above analysis.

Conclusively, the ITWs transmitted to the local-end protection in case of faults on both sides (line side and bus side) of the opposite-end CLR are quite different. The ITW waveforms of internal faults are more similar to that in fault on the line side (200 km) of the opposite-end CLR, while the ITW waveforms of external faults are more similar to that of fault on the bus side of the opposite-end CLR. Therefore, if the

time-domain expressions of the ITWs transmitted to the local-end protection in case of faults on both sides of the opposite-end CLR can be obtained respectively, the measured ITW at the local-end protection can be compared with the waveforms of the above two time-domain expressions to distinguish the internal and external faults.

III. ANALYTICAL CALCULATION OF ITW

Taking the positive pole fault as an example, the time-domain expressions of the ITW transmitted to the local-end protection when the fault occurs on the line side and the bus side of the opposite-end CLR respectively are analyzed.

A. Fault on The Line Side of CLR

The diagram of fault on the line side of the opposite-end CLR is shown in Fig. 6. The electrical quantities of line mode are taken as an example. Since the line parameters are frequency-varying, the analysis is first carried out in the frequency domain, and then converted to the time domain. Since the amplitude of the ITW needs to be normalized, it can be directly taken as -1 for the fault on the positive pole. After line transmission, the frequency-domain expression of the ITW at point M is:

$$\begin{cases} B_{M1}(s) = \frac{-1}{s} A_1(s) \\ A_1(s) = e^{-s\tau_1} \sum_{i=1}^{m_1} \frac{q_{1i}}{s + p_{1i}} \end{cases} \quad (10)$$

where $A_1(s)$ is the transfer function of the line-mode traveling wave; τ_1 is the transmission time of the line-mode traveling wave; m_1 is the number of zeros and poles of the line-mode transfer function; q_{1i} and p_{1i} are the transfer function zeros and poles of the line-mode traveling wave.

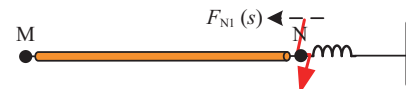


Fig. 6. Fault on the line side of the opposite-end CLR.

By performing Laplace inverse transformation and recursive convolution transformation on (10), the time-domain expression of the line-mode ITW at point M can be obtained as:

$$\begin{aligned} b_{M1}(t) &= \int_{\tau_1}^{+\infty} f_1(t - \mu) f_2(\mu) d\mu \\ &= \int_{\tau_1}^{+\infty} -1(t - \mu) \sum_{i=1}^{m_1} q_{1i} \cdot e^{-p_{1i}(\mu - \tau_1)} d\mu \\ &= \sum_{i=1}^{m_1} [a_{1i} \cdot b_{M1}(t - \Delta t) + b_{1i}(-1(t - \tau_1)) \\ &\quad + c_{1i}(-1(t - \tau_1 - \Delta t))] \end{aligned} \quad (11)$$

where $f_1(t - u)$ and $f_2(u)$ are two functions for recursive convolution; t and u are two variables; a_{1i} , b_{1i} , and c_{1i} are the recursive convolution coefficients of the line mode transfer function; and Δt is the sampling interval.

Similarly, the time-domain expression of the ground-mode ITW can be calculated. Then, the ITW in phase domain when the fault on the line side of the opposite-end CLR can be obtained through the inverse phase-to-mode transformation.

B. Fault on The Bus Side of CLR

The diagram of fault on the bus side of the opposite-end CLR is shown in Fig. 7. In this scenario, the frequency-domain expression of the ITW at point M is:

$$\begin{cases} B_{M1}(s) = \frac{-1}{s} \cdot \frac{Z_{c1}(s)}{Z_{c1}(s) + sL} \cdot A_1(s) \\ A_1(s) = e^{-s\tau_1} \cdot \sum_{i=1}^{m_1} \frac{q_{1i}}{s + p_{1i}} \end{cases} \quad (12)$$

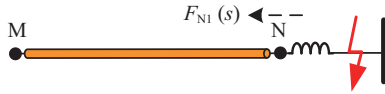


Fig. 7. Fault on the bus side of the opposite-end CLR.

The time-domain expression of the line-mode ITW at point M can be obtained as:

$$\begin{aligned} b_{M1}(t) &= \int_{\tau_1}^{+\infty} f_1(t - \mu) f_2(\mu) d\mu \\ &= \int_{\tau_1}^{+\infty} \left(e^{-\frac{Z_{c1}}{L}(t-\mu)} - 1 \right) \sum_{i=1}^{m_1} q_{1i} \cdot e^{-p_{1i}(\mu-\tau_1)} d\mu \\ &= \sum_{i=1}^{m_1} \left[a_{1i} \cdot b_{M1}(t - \Delta t) + b_{1i} \left(e^{-\frac{Z_{c1}}{L}(t-\tau_1)} - 1 \right) \right. \\ &\quad \left. + c_{1i} \left(e^{-\frac{Z_{c1}}{L}(t-\tau_1-\Delta t)} - 1 \right) \right] \end{aligned} \quad (13)$$

In the same way, the time-domain expression of the ground-mode ITW can be calculated, and the ITW in phase domain when the fault on the bus side of the opposite-end CLR can be obtained.

C. Verification of Time-domain Analytical Results

In the above analytical calculation process, Marti model is used as the line model to calculate the analytical results of the ITW, which can effectively ensure the accuracy and reliability of the analytical waveform. To verify the correctness of the time-domain analytical expressions in Sections III-A and III-B, faults in the line side and bus side of the opposite-end CLR are simulated, respectively. The simulation results are compared with the analytical results, as shown in Fig. 8(a) and Fig. 8(b).

From Fig. 8(a), the analytical value of the fault on the line side of the CLR is close to the simulation value, but there is an obvious difference from the simulation value of the fault on the bus side. As shown in Fig. 8(b), the analytical value of the fault on the bus side is near to the simulation value of the bus side fault but significantly different from the line side fault. Fig. 8 verifies the correctness of the analytical results.

In real operation, the two analytical waveforms of the ITW are calculated in advance and stored in the local protection device. When a fault occurs on the actual line, it is only

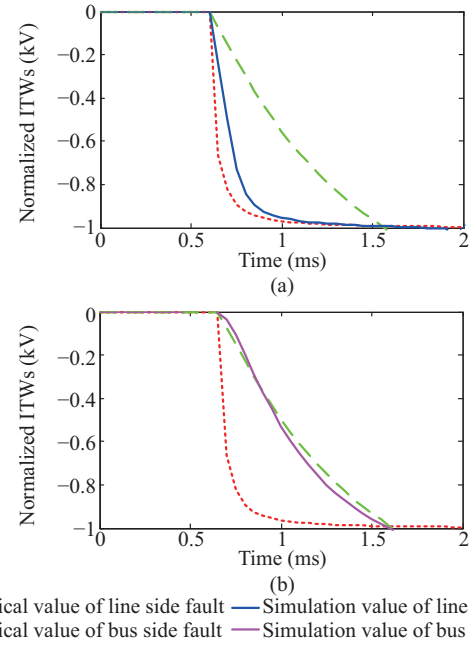


Fig. 8. Verification of time domain analysis results. (a) Line side. (b) Bus side.

necessary to extract the actual waveform of the ITW (which can be calculated by the voltages and currents) at the local protection. Then, the similarities between the actual waveform and the two analytical waveforms in the protection device can be compared to achieve setting-less protection.

IV. SETTING-LESS PROTECTION SCHEME

The functions of protection include fault detection, fault identification, and fault pole selection, which will be described below.

A. Fault Detection

To avoid frequent detection, it is necessary to design a fault detection criterion. At present, the research on fault detection criteria has been relatively mature, and the typical ones in engineering include voltage change rate and current change rate [10], [11], [25]. In this paper, the voltage change rate criterion is selected as the fault detection criterion, shown as follows:

$$\left| \frac{du_M}{dt} \right| > u_{set} \quad (14)$$

where u_M is the measured voltage at the local-end protection; u_{set} is the threshold of fault detection criterion, which is set by referring to the existing projects [25].

B. Fault Identification

According to the analysis in Sections II and III, internal similarity S_{internal} and external similarity S_{external} are defined as:

1) S_{internal} : Similarity between the measured ITW at the local-end protection and the analytical ITW transmitted to the local-end protection in case of fault on the line side of the opposite-end CLR;

2) S_{external} : Similarity between the measured ITW at the local-end protection and the analytical ITW transmitted to the local-end protection in case of fault on the bus side of the opposite-end CLR.

The similarity is examined by Pearson similarity [26], which is expressed as follows:

$$S = \frac{\sum_{i=1}^N \left(X_i - \frac{1}{N} \sum_{j=1}^N X_j \right) \left(Y_i - \frac{1}{N} \sum_{j=1}^N Y_j \right)}{\sqrt{\sum_{i=1}^N \left(X_i - \frac{1}{N} \sum_{j=1}^N X_j \right)^2} \sqrt{\sum_{i=1}^N \left(Y_i - \frac{1}{N} \sum_{j=1}^N Y_j \right)^2}} \quad (15)$$

where X_i is the measured ITW; Y_i is the analytical ITW; N is the number of points used for similarity calculation; i and j are variables.

When S_{internal} is greater than S_{external} , the internal fault is judged, otherwise, the external fault is judged. The protection operation criterion is expressed as:

$$S_{\text{internal}} > S_{\text{external}} \quad (16)$$

To avoid protection maloperation caused by disturbance such as lightning, it is specified that if (16) are met 5 consecutive times, the internal fault is judged, and the protection operates. Otherwise, the protection will not operate. The proposed scheme only needs to compare S_{internal} and S_{external} to realize the setting-less protection without setting threshold and reliability coefficient.

C. Faulty Pole Selection

For positive pole-to-ground faults (PGF), the ground-mode ITWs show a fast-falling trend; for negative pole-to-ground faults (NGF), the ground-mode ITWs show a fast-rising trend; For pole-to-pole faults (PPF), the ground-mode ITWs do not exist (theoretically 0). Based on the above characteristics, the faulty pole selection criterion is proposed as follows:

$$\begin{cases} \text{P-G: } b_{M0} < -k_{\text{set}} b_{M0\text{set}} \\ \text{N-G: } b_{M0} > k_{\text{set}} b_{M0\text{set}} \\ \text{P-P: } -k_{\text{set}} b_{M0\text{set}} \leq b_{M0} \leq k_{\text{set}} b_{M0\text{set}} \end{cases} \quad (17)$$

where $b_{M0\text{set}}$ is the threshold of the ground-mode ITW, and k_{set} is the reliability coefficient of the faulty pole selection criterion. Since the amplitude of the ITW decreases with the increase of the transition resistance, the minimum amplitude of $b_{M0\text{set}}$ is 300 kV in case of high resistance fault (500 Ω). Since b_{M0} is very small and almost zero in the case of PPF, k_{set} is set to 0.3 in consideration of a certain margin and the rapidity of faulty pole selection.

D. Overall Process

The overall flow chart of the protection scheme is shown in Fig. 9. Voltage traveling wave is the electrical quantity adopted in this paper, and ITW refers to the initial voltage traveling wave. The specific process is described as follows:

1) The protection starts up, and the phase-to-mode transformation matrix is used to decouple the voltages and currents at local-end protection;

2) Obtain the line-mode and ground-mode ITWs at local-end protection by (6). The inverse phase-to-mode transformation is performed to obtain the measured value $b_{M\text{real}}$ of the ITW;

3) Normalize the measured value $b_{M\text{real}}$, calculate and compare the S_{internal} and S_{external} ;

4) If $S_{\text{internal}} > S_{\text{external}}$ is satisfied 5 consecutive times, the internal fault is judged, otherwise the external fault is judged.

5) Use the ground-mode ITW to select the faulty pole. If $b_{M0} < -k_{\text{set}} b_{M0\text{set}}$, the PGF is judged; if $b_{M0} > k_{\text{set}} b_{M0\text{set}}$, the NGF is judged; if $-k_{\text{set}} b_{M0\text{set}} \leq b_{M0} \leq k_{\text{set}} b_{M0\text{set}}$, the PPF is judged.

It should be noted that the internal and external similarities at judgment points after the first five judgment points may coincide or even reverse since the wave tail of the ITWs under both internal and external faults tends to be flat, thus affecting the reliability of the proposed protection scheme. Therefore, only the similarities of the first five points are calculated in this scheme. After the five points, the similarity calculation is terminated. In the five judgment points, if the internal similarity is greater than the external similarity at each point, the internal fault is judged. Otherwise, the external fault is judged.

V. ANALYSIS OF INFLUENCING FACTORS

A. Transition Resistance

It can be seen from the analysis in Section II-A that the transition resistance only affects the amplitude of the ITW, but does not affect its waveform shape. Normalization can eliminate the influence of transition resistance. Therefore, the proposed scheme has better tolerance to transition resistance.

B. Fault Location

The fault location mainly affects the distortion and arrival time of the ITW. The farther the fault location is from the local-end protection, the more serious the distortion of the ITW is. With increase of fault distance, the distortion of the ITW changes monotonically, and the difference of the ITW is significant when faults occur on both sides of the opposite-end CLR. The proposed scheme takes advantage of the natural boundary formed by the CLR. For internal faults, S_{internal} is always greater than S_{external} ; for external faults, S_{internal} is always less than S_{external} . Therefore, the fault location does not affect the reliability of the proposed scheme.

C. Lightning Disturbance

The generally recognized 1.2/50 μs double exponential lightning current model is adopted to simulate lightning disturbance [27]. The expression of the lightning current model is:

$$i(t) = k_c I_p (e^{-\alpha t} - e^{-\beta t}) \quad (18)$$

where k_c is the waveform correction coefficient, $k_c = 1.03725$; I_p is the lightning current amplitude, $I_p = 15$ kA; α and β are the attenuation coefficients of the lightning current wave head and wave tail, respectively, $\alpha = 2.4689 \mu\text{s}^{-1}$, $\beta = 0.014659 \mu\text{s}^{-1}$.

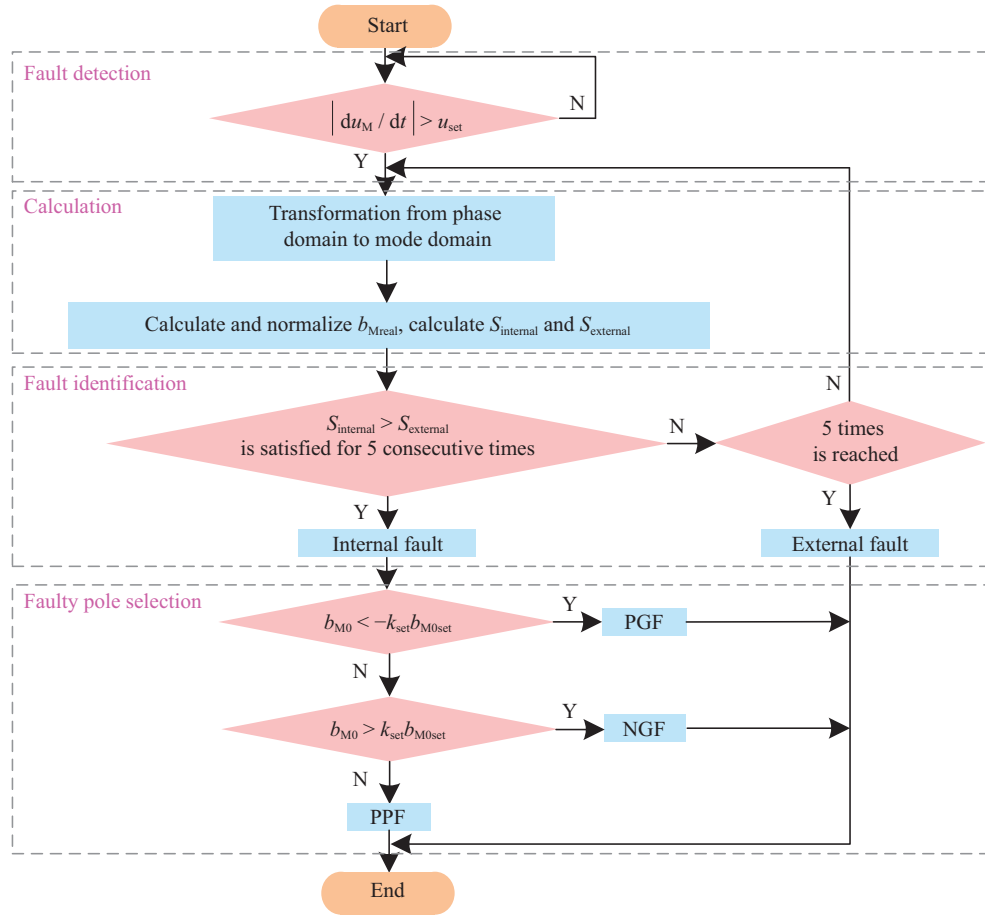


Fig. 9. Overall flow chart of the protection scheme.

The standard lightning current waveform is shown in Fig. 10. It can be seen that the wave head of the lightning current is similar to the wave head of the ITWs under internal faults. However, the wave head duration of the lightning current is only $1.2 \mu\text{s}$, which is extremely short. The sampling interval in this paper is $50 \mu\text{s}$. Therefore, to eliminate the disturbance of lightning current, it is stipulated that if the fault identification criterion is met 5 consecutive times, the internal fault is judged. Multiple judgments can ensure the reliability of the proposed scheme.

D. Noise

Noise will reduce the similarity between two signals. When there is noise in the measured ITW, both S_{internal} and S_{external} in the proposed scheme will decrease. Moreover, this will not change the result that $S_{\text{internal}} > S_{\text{external}}$ under internal faults and $S_{\text{internal}} < S_{\text{external}}$ under external faults. Therefore, the proposed scheme has a certain anti-noise ability.

E. Sampling Frequency

The sampling frequency mainly affects the calculation step, thus affecting the operation time of the protection scheme. Besides, it also has a certain requirement on the computing power of the computer. Therefore, the setting of sampling frequency should consider both protection quickness and calculation performance. In the real project, the sampling frequency of

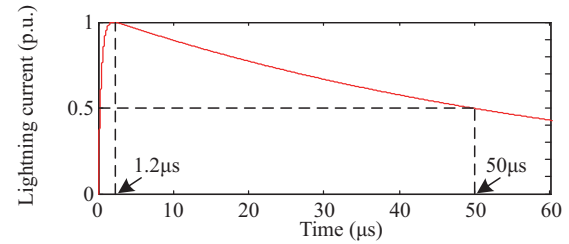


Fig. 10. Standard lightning current waveform.

protections is as high as 50 kHz [22]. Instead, the protection scheme proposed in this paper can be implemented at the sampling frequency of only 20 kHz, which can simultaneously meet the requirements of protection quickness and calculation performance. Therefore, the sampling frequency is set as 20 kHz.

F. Communication Transmission

In the proposed scheme, the two ITW analytical waveform data (faults on the line side and bus side of the opposite-end CLR) should be stored in the local protection in advance. When the fault occurs, only the ITW at the local protection needs to be extracted to calculate S_{internal} and S_{external} . Namely, the proposed scheme is only implemented by single-ended information and no double-ended information

is required. Therefore, it is not affected by communication transmission.

G. Length of Transmission Line

The line length will affect the arrival time of ITW, thus affecting the operation time of protection. The transmission speed of ITW is usually $2.998 \times 10^8 \text{ m/s}$ [28], and VSC-MTDC grids usually require protection to operate within 3 ms. In addition, the time window and fault identification time of the proposed protection scheme is 0.5 ms in total. So theoretically, the applicable line length of the scheme is:

$$(3 - 0.5) \times 10^{-3} \times 2.998 \times 10^8 = 749.5 \text{ km} \quad (19)$$

Considering a certain margin, it is believed that the scheme can be applied to lines with a length of less than 700 km.

H. CLR

The ITW will be refracted after passing through the CLR. The larger the inductance value of the CLR, the stronger the refraction effect on the ITW, and the more serious the distortion of the ITW. When the fault occurs on the line side and bus side of the opposite-end CLR respectively, there will be an obvious difference in the ITWs transmitted to the local-end protection. The proposed scheme uses the difference generated by the refraction of the CLR to distinguish the internal and external faults. Referring to the parameters of the Zhangbei four-terminal VSC-HVDC grid [29], the CLR is selected as 150 mH in this paper.

I. Time Window and Judgment Time

The time window refers to the time length of signals used for similarity calculation. The selection of the time window is mainly based on the accuracy of similarity calculation. Due to the complexity of the similarity formula, the time window cannot be obtained through theoretical calculation. Therefore, simulation experience is a desirable method. According to a large amount of simulation comparison, 0.3 ms is the best time window for similarity calculation.

The judgment time depends on the number of judgment points, and the selection basis mainly considers the following two aspects: 1) The influence of lightning disturbance on protection criterion should be avoided. 2) The difference between internal similarity and external similarity should be considered. Considering comprehensively, the judgment results of the first five consecutive times are selected for judgment. In this paper, the sampling frequency is 20 kHz, and the calculation step is 50 microseconds. Therefore, the total time of the five consecutive judgment points is 0.2 ms, which is the judgment time.

VI. SIMULATION AND VERIFICATION

A. Test System

To examine effectiveness of the proposed protection scheme, Zhangbei four-terminal VSC-HVDC grid is used as test network which its topology is shown in Fig. 11. AC1-4 are AC power sources, MMC1-4 are converter stations, and OHL1-4 are overhead lines. The outlets at both ends of the lines are

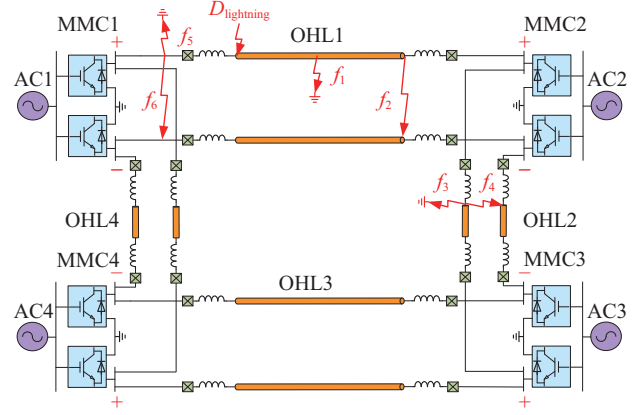


Fig. 11. Zhangbei four-terminal VSC-HVDC grid.

equipped with CLR. The detailed parameters of the networks are selected according to [29]. The faults occur at 0 ms. The OHL1 is taken as an example, the line length is 200 km. f_1 – f_5 and $D_{\text{lightning}}$ are described as follows:

f_1 : PGF with 100Ω transition resistance at the midpoint of OHL1; f_2 : metallic PPF at the end of OHL1; f_3 : PGF with 100Ω transition resistance at the head of OHL2; f_4 : metallic PPF at the head of OHL2; f_5 : metallic PGF at the bus side of the local-end CLR; f_6 : metallic PPF at the bus side of the local-end CLR; $D_{\text{lightning}}$: lightning disturbance at the head of OHL1.

B. Protection Scheme Verification

This section verifies the effectiveness of the proposed scheme under different faults.

1) Internal Fault

Internal faults f_1 and f_2 are taken as examples for verifying the effectiveness of the scheme under internal faults. Fig. 12 is the identification results of fault f_1 , and Fig. 13 is the identification results of fault f_2 .

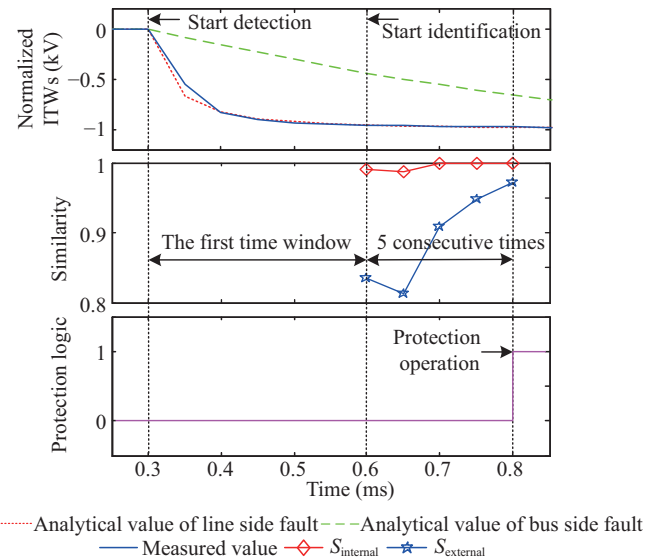
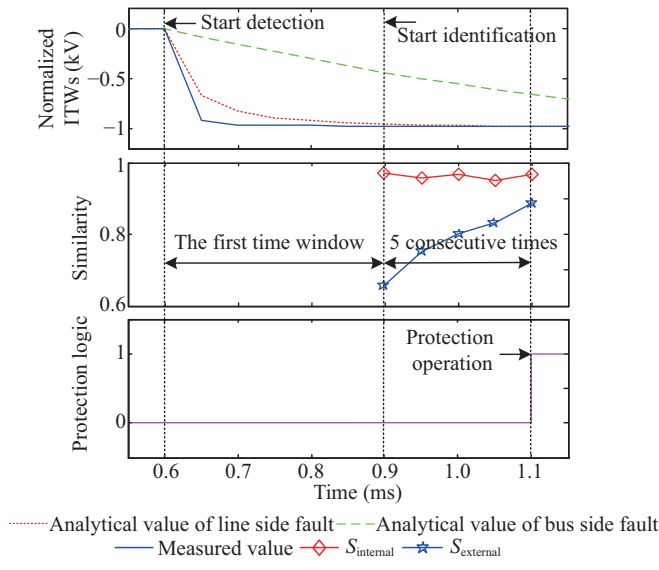


Fig. 12. The identification results of fault f_1 .


 Fig. 13. The identification results of fault f_2 .

It can be seen from Fig. 12 that the time for the ITW reach to the local-end protection is 0.3 ms. Compared to the analytical waveform of the fault on the bus side of the opposite-end CLR, the measured waveform of the ITW is similar to the analytical waveform of the fault on the line side of the opposite-end CLR. Since the first time window (0.3 ms) for similarity calculation needs to be waited on, fault identification starts at 0.6 ms. Then, the S_{internal} of the following 5 consecutive points is always greater than the S_{external} , which satisfies the protection operation criterion. The protection operates at 0.8 ms. The proposed scheme can identify the internal PGFs.

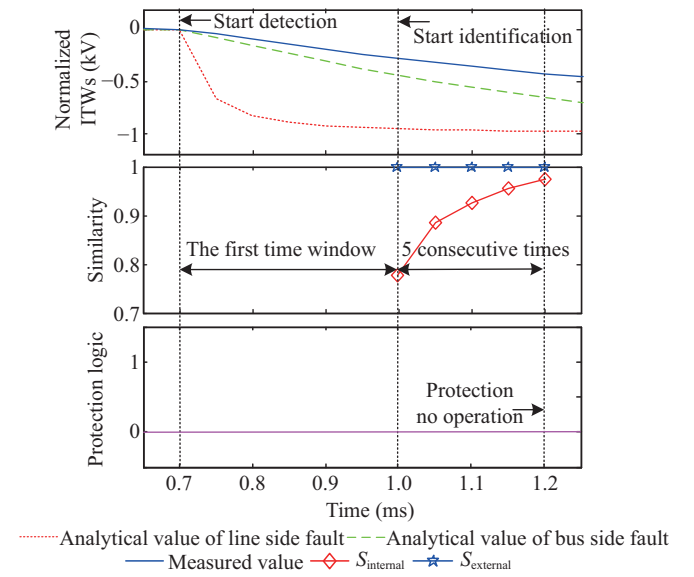
Compared with fault f_1 , the location of fault f_2 is farther. Hence, the arrival time of the ITW is also later, which is 0.6 ms in Fig. 13. Like the PGF, the measured waveform of the ITW is more similar to the analytical waveform of the fault on the line side of the opposite-end CLR. The fault identification starts at 0.9 ms, and the internal fault criterion $S_{\text{internal}} > S_{\text{external}}$ is satisfied 5 consecutive times. The protection operates at 1.1 ms, and the proposed scheme can identify internal PPFs.

2) External Fault

External faults include forward external faults and backward external faults, which are verified as follows.

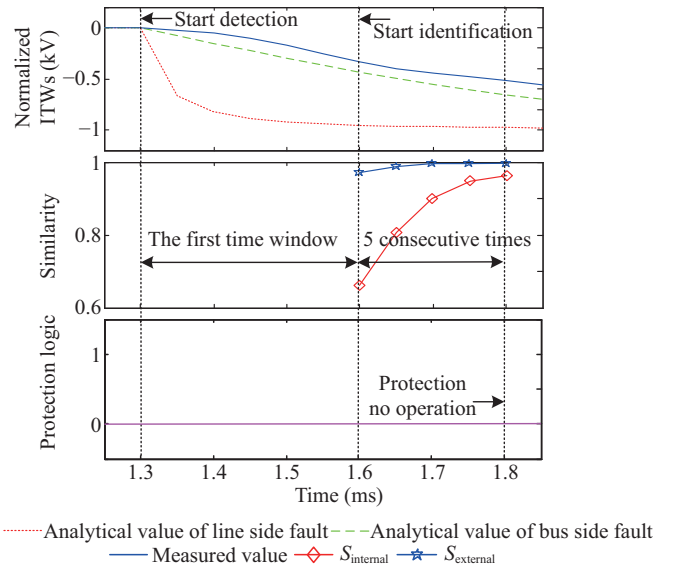
a) *Forward external faults:* The faults f_3 and f_4 are taken as examples for verifying the effectiveness of the scheme under forward external faults. Fig. 14 is the identification results of fault f_3 .

From Fig. 14, the time for the ITW reach to the local-end protection of OHL1 is 0.7 ms. Compared to the analytical waveform of the fault on the line side of the opposite-end CLR of OHL1, the measured waveform of the ITW is similar to the analytical waveform of the fault on the bus side of the opposite-end CLR of OHL1. At 1.0 ms, fault identification starts. The S_{internal} of the following 5 consecutive points is always less than the S_{external} . The external fault is judged at 1.2 ms. The protection will not operate. The proposed scheme can identify external PGFs. Similarly, external PPFs can also be reliably identified. The identification result of fault f_4 will


 Fig. 14. The identification results of fault f_3 .

not be shown here. The above results verify the effectiveness of the proposed protection scheme for forward external faults.

b) *Backward external faults:* The faults f_5 and f_6 are taken as an example to verify effectiveness of backward external faults. Fig. 15 is the identification results of fault f_5 .


 Fig. 15. The identification results of fault f_5 .

For backward external faults, the ITWs are refracted by the local-end CLR and transmitted to the local-end protection by twice the full length of OHL1. Therefore, it should also satisfy the conclusion that S_{external} is greater than S_{internal} . From Fig. 15, the time for the ITW to reach local-end protection is 1.3 ms. The measured waveform of the ITW is more similar to the analytical waveform of the fault on the bus side of the opposite-end CLR. The fault identification starts at 1.6 ms, and the S_{internal} of the following 5 consecutive points is smaller than the S_{external} . At 1.8 ms, the external fault is judged, and the protection will not operate. A similar analysis is also valid

for fault f_6 , which is not shown here. Therefore, backward external faults can also be reliably identified.

C. Influence of Transition Resistance

To verify the influence of transition resistance on internal and external faults, PGFs with different transition resistances (0 Ω , 300 Ω , 500 Ω) are set, respectively, at the midpoint of OHL1 and the head of OHL2. S_{internal} and S_{external} of the 5 consecutive judgment points are shown in Fig. 16. Fig. 16(a) and Fig. 16(b) are the results of internal and external faults, respectively.

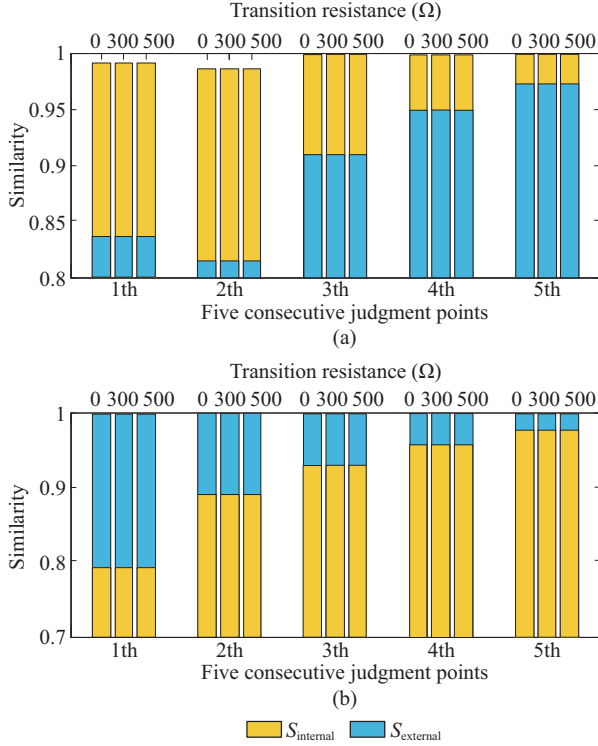


Fig. 16. Influence verification of transition resistance. (a) Internal faults. (b) External faults.

It is not difficult to see from Fig. 16(a) that the S_{internal} of each judgment point is roughly the same under different transition resistances and the S_{external} is also the same. This verified again the conclusion in Section II-A. The S_{internal} of the five consecutive judgment points in Fig. 16(a) is always higher than the S_{external} , which can reliably identify internal faults. For external faults as shown in Fig. 16(b), the S_{internal} or the S_{external} of each judgment point is also the same under different transition resistances. S_{internal} of the five consecutive judgment points is lower than the S_{external} , so external faults can also be identified. Therefore, the proposed scheme has adequate tolerance for transition resistance.

D. Influence of Fault Location

Different metallic faults are set at different locations on OHL1. PGFs and PPFs with 500 Ω transition resistance are set, respectively, at the head of OHL2 and the bus side of the local-end CLR, expressed as $f_3(500 \Omega)$, $f_4(500 \Omega)$, $f_5(500 \Omega)$, $f_6(500 \Omega)$. The simulation results are shown in Table I.

TABLE I
SIMULATION RESULTS OF FAULTS AT DIFFERENT LOCATIONS

Fault type	Fault location (km)	$S_{\text{internal}} > S_{\text{external}}$ is satisfied for 5 consecutive times	Operation time (ms)	Result
PGF	0	Y	0.50	Internal fault
	50	Y	0.60	Internal fault
	100	Y	0.80	Internal fault
	150	Y	0.95	Internal fault
	200	Y	1.10	Internal fault
	$f_3(500 \Omega)$	N	–	External fault
	$f_5(500 \Omega)$	N	–	External fault
PPF	0	Y	0.50	Internal fault
	50	Y	0.60	Internal fault
	100	Y	0.80	Internal fault
	150	Y	0.95	Internal fault
	200	Y	1.10	Internal fault
	$f_4(500 \Omega)$	N	–	External fault
	$f_6(500 \Omega)$	N	–	External fault

From Table I, the protection operation time is the same whether it is a PGF or a PPF. With increase of the fault distance, the protection operation time will also become longer. The reason is that the farther the fault location is from the local-end protection, the longer the arrival time of the ITW, thus making the protection operation time correspondingly longer. For 200 km lines, the maximum protection operating time is 1.1 ms, which meets the requirement for the protection of VSC-MTDC grids. For external faults, the protection will not operate. Therefore, the rapidity and reliability of the proposed scheme under different fault locations can be guaranteed.

E. Influence of CLR

The inductance value of CLR in the VSC-MTDC grid is usually 100–200 mH [30]. To verify the influence of the CLR on the protection scheme, the ITWs of different CLRs are compared, respectively. The faults are set on the bus side of the opposite-end CLR, and the transition resistance is 300 Ω . The simulation results are shown in Fig. 17.

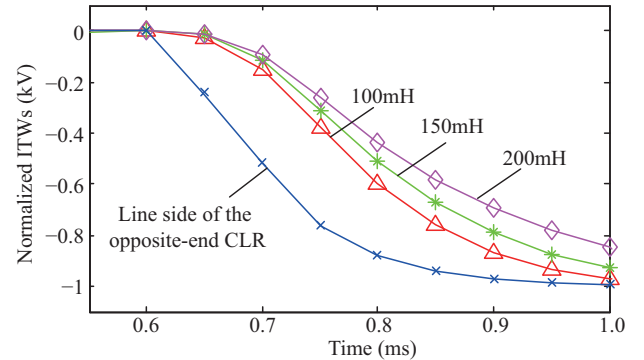


Fig. 17. ITWs of different CLRs.

From Fig. 17, while the inductance values of the CLR increase, the distortion of the ITWs transmitted to the local-end protection is also larger, which again verifies the rationality of Section II-B. Since the distortion of the ITWs is larger, the difference between them and the ITW transmitted to the local-end protection in case of fault on the line side of the

opposite-end CLR is also larger, which is more conducive to distinguish the internal and external faults. That is, the larger the inductance value of the CLR is, the performance of the protection scheme is better. In this paper, the value of the CLR is set at 150 mH, which can meet the needs of the protection scheme.

F. Verification of Lightning Disturbance

Take $D_{\text{lightning}}$ as an example to verify the influence of lightning disturbance on protection. The lightning disturbance is added to the normal working line at 0 ms. The results of fault identification are shown in Fig. 18. It can be seen that the S_{internal} of the first two judgment points is greater than the S_{external} , and the S_{internal} of the last three judgment points is smaller than the S_{external} , which does not satisfy the $S_{\text{internal}} > S_{\text{external}}$ for five consecutive judgment points. Therefore, the internal fault criterion is not met, and the protection will not operate.

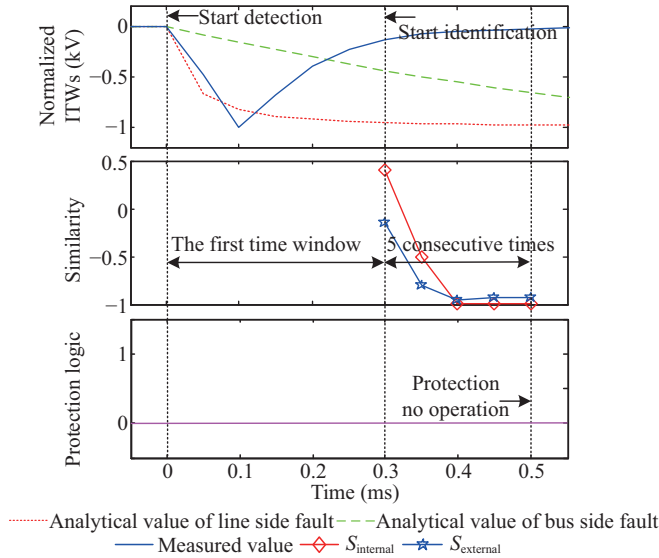


Fig. 18. The identification results under disturbance $D_{\text{lightning}}$.

G. Verification of Noise

The actual signal will contain noise, and the noise will reduce the similarity between the signals. Therefore, it is necessary to analyze the influence of noise on protection performance. Taking fault f_1 as an example, 30 dB noise is added to the measured ITW. The simulation results are shown in Fig. 19.

It can be readily seen from Fig. 19 that the noise will lead to a decrease in both S_{internal} and S_{external} . However, it is

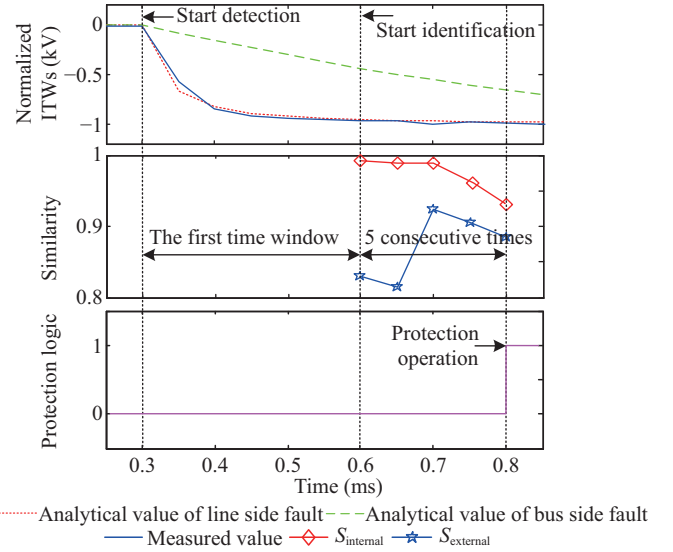


Fig. 19. The identification results under 30 dB noise.

still satisfied that the S_{internal} is greater than the S_{external} 5 consecutive times. The internal faults can still be identified, and the protection can operate reliably. The proposed scheme can withstand 30 dB noise.

H. Superiority Comparison

To highlight superiority, the proposed scheme is compared with several existing schemes.

1) Comparison with Typical Methods

The typical methods can be divided into double-ended protections and single-ended protections. The comparison results are shown in Table II. Compared with [10], [12], the proposed scheme operates faster and does not require communication. The proposed scheme has better anti-noise performance compared with [14]. Compared with [15] and [16], the proposed scheme has lower requirements on sampling frequency. In addition, compared with the above schemes, the performance of the proposed scheme does not rely on threshold setting, and is not affected by the transition resistance.

2) Comparison with Other Waveform Correlation-based Methods

The scheme proposed in this paper employs waveform correlation to realize the protection criterion. However, some existing methods also employ waveform correlation as a tool. To highlight the advantages of the proposed scheme, the following is a comparative analysis. In [17]–[19], waveform correlation characteristics of different electrical quantities are

TABLE II
COMPARISON WITH OTHER PROTECTION SCHEMES

Schemes	Double-ended protections			Single-ended protections		The proposed scheme
	[10]	[12]	[14]	[15]	[16]	
Threshold setting is required	Yes	Yes	Yes	Yes	Yes	No
Operation time	3–4 ms	–	1.5 ms	Microsecond level	1.2 ms	1.1 ms
Anti-transition resistance performance	300 Ω	300 Ω	300 Ω	300 Ω	300 Ω	Not affected by transition resistance
Communication is required	Yes	Yes	No	No	No	No
Acceptable maximum noise	–	–	35 dB	–	Remove noise	30 dB
Sampling frequency	20 kHz	10 kHz	–	200 kHz	1 MHz	20 kHz

selected, respectively, to identify internal and external faults. In these methods, a common defect is performance of the protection schemes depends on the threshold setting. In [11], a similarity comparison-based pilot protection scheme is proposed adopting the cross-wavelet transform, but the quickness of protection is an unavoidable issue that needs to be improved. A non-unit protection method using waveform correlation calculation is proposed in [13], which has high operation speed. However, the benchmark, which is obtained by simulation, lacks theoretical support. Furthermore, threshold settings still exist in [11] and [13]. The key idea of our proposed scheme is “setting-less” protection, that is, the fault zone can be identified by only comparing the internal similarity and the external similarity and no threshold setting, which is the largest advantage compared with the above waveform correlation-based methods. Moreover, time-domain expressions of the ITW are deducted considering the frequency-varying characteristics of the line distribution parameters, which can provide theoretical support for ITW analysis.

3) Comparison with Other Setting-less Protection methods

Protection performance depending on the threshold setting is a challenging issue in the project, and the existing research is relatively small. Scholars in [22] and [23] tried proposing setting-less line protection and component protection. However, performance of the above schemes will be affected by the transition resistance. In our setting-less protection scheme, the normalization process on the ITW can effectively eliminate the influence of transition resistance since the transition resistance only affects the amplitude of the ITW but does not affect its waveform. Therefore, the proposed scheme has adequate tolerance for transition resistance compared with the existing setting-less protections.

VII. CONCLUSION

In this paper, a setting-less protection scheme based on the waveform characteristics of the ITW is proposed for VSC-MTDC grids. The scheme has the following advantages:

1) Setting less: The proposed scheme only needs to compare the S_{internal} and the S_{external} to identify internal and external faults, and there is no threshold setting. It solves the problem of protection maloperation caused by improper threshold setting from the root, and greatly improves performance of the protection.

2) High speed: Since the proposed scheme is only implemented with single-ended quantities and does not require double-ended communication, the protection operation is fast. For lines with a length of 200 km, the protection can operate within 1.1 ms.

3) Strong robustness: The normalization process effectively eliminates the influence of the transition resistance, and the proposed scheme is not affected by fault location and noise. Consecutive judgments effectively avoid misjudgment caused by lightning disturbance.

Since the proposed scheme contains the normalization link, the amplitude of the ITW is directly replaced by -1 . Hence there is a certain error between the analytical waveform and the actual waveform of ITW. Therefore, the next work by

the authors is to enhance the analytical calculation accuracy of the proposed protection scheme. Moreover, we will also implement hardware in the loop test to further verify the feasibility of the proposed scheme.

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Meng Li received the B.S. and Ph.D. degrees in Electrical Engineering from North China Electric Power University, Beijing, China, in 2003 and 2018, respectively. He is currently an Associate Professor with the School of Electrical Engineering, Beijing Jiaotong University, Beijing, China. His research interests include DC grid fault analysis, protection, and recovery.



Jiaxing Ning received the M.S. degree in Electrical Engineering from Shandong University of Technology, Zibo, China, in 2019. He is currently working toward the Ph.D. degree in Electrical Engineering with the Department of Electrical Engineering, Beijing Jiaotong University, Beijing, China. His research interests include protection principle, arc model, and adaptive recovery in AC/DC power system.



Jinghan He received the M.Sc. degree in Electrical Engineering from Tianjin University, Tianjin, China, in 1994, and the Ph.D. degree in Electrical Engineering from Beijing Jiaotong University, Beijing, China, in 2007. Since 2000, she has been a Professor with the School of Electrical Engineering, Beijing Jiaotong University. Her research interests include AC–DC power system protection and control, monitoring, and protection of the railway traction power supply systems. Dr. He is currently a Chairman of IEEE Power and Energy Society (PES) China Membership Committee and a member of DC System Protection and Control Working Group under the IEEE PES China Subcommittee.



Sohrab Mirsaeidi received the Ph.D. degree in Electrical Engineering from Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 2016. From 2016 to 2019, he furthered his Postdoctoral Fellowship with the Department of Electrical Engineering, Tsinghua University, Beijing, China. He is currently an Associate Professor with the School of Electrical Engineering, Beijing Jiaotong University, Beijing, China. He has authored or coauthored more than 50 papers and two books in the field of microgrids and large-scale power systems. His main research interests include control and protection of large-scale hybrid AC/DC grids and microgrids, power system stability, and application of power electronics in power systems. He is a Member of the IET, CIGRE, and Chinese Society for Electrical Engineering.



Ming Nie received the M.Sc. degree in Electrical Engineering in 2020 from Beijing Jiaotong University, Beijing, China, where he is currently working toward the Ph.D. degree in Electrical Engineering. His research interests include DC grid protection and control.