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A New Differential Protection for Transmission Lines Connecting Renewable Energy Sources to MMC-HVDC Converter Stations Based on Dynamic Time Warping Algorithm

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***Abstract*—There are electronic controlled power sources on both sides of the transmission line, which connects the renewable energy sources (RES) station and the modular multilevel converter high-voltage DC (MMC-HVDC) converter station. The control strategy affects the fault characteristics of the short-circuit current, making it amplitude-limited and phase-angle-controlled. The sensitivity performance of the original line differential protection decreases, and the adaptability of the protection needs to be further studied. Aiming at this problem, the fault characteristics of short-circuit current fed from the RES station and the MMC-HVDC converter station are both analyzed. And a differential protection method based on dynamic time warping is proposed. The distance matrix is constructed by calculating the Euclidean distance of the currents. Then calculate the shortest cumulative distance which is used to characterize the waveform similarity of the current and construct protection criteria based on waveform similarity. Through simulation and calculation, the effectiveness of the proposed protection method is verified, showing that the protection algorithm can sensitively identify internal and external faults.**

Keywords*—renewable energy sources; modular multilevel converter; HVDC transmission; dynamic time warping; waveform similarity; line differential protection

I. INTRODUCTION

In recent years, the contradiction between environmental protection and energy shortage has become increasingly prominent. Renewable energy sources (RES) power generation has received more attention and related technologies have been developed rapidly. It's becoming an important way that RES such as wind power and photovoltaics(PV) is connected to the grid through the modular multilevel converter high-voltage DC (MMC-HVDC) transmission system because of its advantages of flexible power control and the ability to provide voltage support for passive networks[1]. Wind turbines and photovoltaics power are usually boosted by inverters, and then connected to MMC-HVDC converter stations through AC transmission lines[2]. There are electronic controlled power sources on both sides of the transmission line, which has the characteristics of double-side weak feeder lines. Different from the conventional AC system of synchronous generator power supply, the weak characteristic of short-circuit current will seriously impair the operating performance of differential protection. In severe cases, there may be a risk of protection rejection or action return, which affects the safe operation of the system and the stable delivery of RES[3].

The existing achievements in the related research field are reflected in the analysis of the influence of the controlled

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power source at both sides and the proposal of a new protection principle.

On the one hand, it mainly studies the analysis of the influence of RES inverters on fault characteristics and constructs new protection methods. Some scholars have found that the fault characteristics of the inverter-type power supply and the synchronous generator power supply are completely different. The amplitude of the short-circuit current is limited, the power angle is controlled and the frequency is offset[4], which leads to the risk of rejection of the differential protection. Some scholars have proposed new protection methods suitable for RES transmission lines. The article uses the Pearson correlation coefficient to measure the waveform similarity to construct a differential protection criterion to identify faults[5]. The article identifies the faults inside and outside the area by judging the change of the ratio of the low-frequency energy to the high-frequency energy in the differential current during the fault[6]. The article uses the edge detection algorithm to identify the variation of the current[7], and uses the average gradient to construct the action equation.

On the other hand, most scholars have studied the fault analysis and protection method optimization of the grid-side AC line in the MMC-HVDC transmission system. In this case, one end of the line is the MMC-HVDC converter station, and the other end is the grid system of the equivalent synchronous generator. Only one side is a controlled power electronics supply, unlike the case where RES is sent out through MMC converter. Based on the actual engineering of RES, some scholars have analyzed that when the AC power grid fails, the fault ride-through control strategy will inhibit the short-circuit current fed by the converter[8]. Some scholars went a further step and analyzed the influence mechanism of the control characteristics of the MMC-HVDC converter on the differential protection from the circuit structure. It is considered that the operation mode, control strategy and the outer loop control link of the converter affects the magnitude of the short-circuit current. And an improved strategy is proposed for the protection in the end[9-10].

However, the research on the protection of the controlled electronic power supply on both sides of the line is not in-depth and comprehensive. The relevant research achievements are not applicable to the transmission line with double-ended weak feeder[11-14]. Therefore, it's necessary to study new strategies for AC line protection of RES access to MMC-HVDC converter stations, so as to be suitable for various fault conditions.

Based on analysis for the fault characteristics of the transmission line, this paper introduces a dynamic time warping (DTW) algorithm to solve the problem of the sensitivity reduction or rejection action of the transmission line differential protection. The Euclidean distance matrix is constructed by using the sampling short-circuit current. Calculate the shortest cumulative distance of the matrix and obtain the current waveform characteristics. A new principle for the protection of RES transmission lines connected to MMC-HVDC converter stations based on DTW distance metric is proposed. The simulation and calculation results show that the proposed protection method can reliably extract the waveform fault characteristics and accurately identify internal and external faults, which verifies the effectiveness of the new differential protection.

II. Analysis of Fault Characteristics of Transmission Lines

Fig.1 shows the typical wiring diagram of the RES station sent through the MMC-HVDC transmission system. In this paper, the research object is the 220kV AC transmission line between the RES station and the MMC-HVDC transmission system. When a fault occurs on the line, the short-circuit current is provided by the RES station side and the MMC-HVDC rectifier converter station side respectively. RES stations generally include wind turbines, PVs and other power sources, which are connected to the grid by inverters.

A. Fault Characteristics on the RES Station Side

The fault characteristics are determined by the control strategy of the inverter. After the fault occurs, in order to suppress the negative sequence current, the inverter adopts a low voltage ride-through control strategy. The short-circuit current provided by the inverter side under any type of fault does not contain negative sequence components. For the step-up transformer of the RES station, the high-voltage side often adopts the star grounding method [15]. When a ground fault occurs, the fault zero-sequence network only includes the line grounding point to the step-up transformer grounding point. Only the positive sequence component is fed from the RES station. The expression of the short-circuit current from the inverter to the line $i_{RES\varphi}$ is as follows [16-17]:

$$\begin{aligned} i_{RES\varphi} &= i_d^* \cos(\omega t+\theta_\varphi) - i_q^* \sin(\omega t+\theta_\varphi) \\ &+(i_{d0}-i_{d+}^*)\frac{\mathrm{e}^{-\zeta\omega_n t}\sin(\omega_\mathrm{d} t+\beta)}{\sqrt{1-\zeta^2}}\cos(\omega t+\theta_\varphi) \\ &+i_{q+}^*\frac{\mathrm{e}^{-\zeta\omega_n t}\sin(\omega_\mathrm{d} t+\beta)}{\sqrt{1-\zeta^2}}\sin(\omega t+\theta_\varphi) \end{aligned} \tag{1}$$

Where i_Φ is the φ phase fault current fed by the inverter; i_d^*, i_q^* are the reference current d-axes and q-axes. Under the negative sequence suppression control strategy, $i_d^* = i_{d+}^* = u_{d+}\cdot P_0^*/U_P + u_{q+}\cdot Q_0^*/U_Q$, $i_q^* = i_{q+}^* = u_{q+}\cdot P_0^*/U_P - u_{d+}\cdot Q_0^*/U_Q$, P_0^*, Q_0^* are the active and reactive power reference values and u_{d+}, u_{q+} are the positive sequence of d-axis voltages and q-axis voltages on the grid-connected point. i_{d0} is the d-axis reference current before the fault, θ_ϕ is the initial fault phase angle; ζ is the damping ratio of the second-order system; ω_n is the natural oscillation angular frequency of the second-order system; ω_d is the damping oscillation frequency; β is the damping angle; ω is the fundamental angular frequency.

In (1), the magnitude of the short-circuit current fed from the RES station is controlled. The inverter only provides positive sequence current and the reference values of its positive sequence d-axis and q-axis are given by the control limiting loop. When the voltage drops greatly, the short-circuit current d-axis and q-axis components will reach the upper limit of the control reference value.

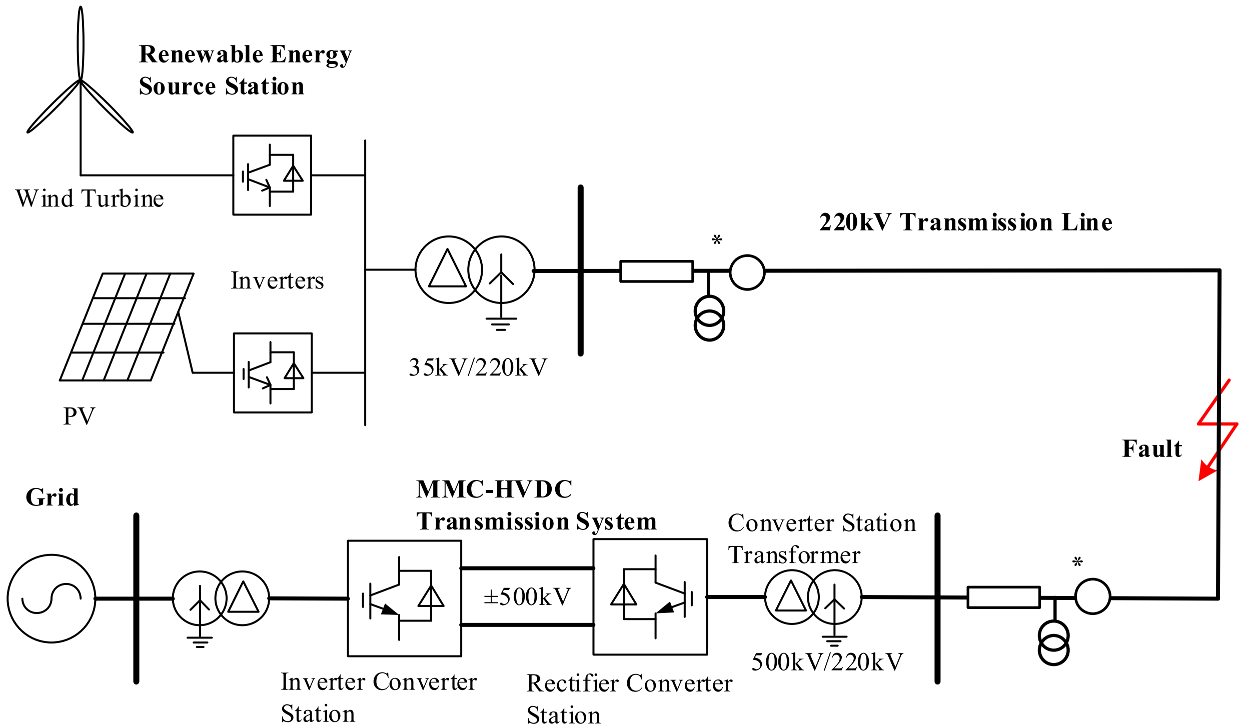

Fig.1. Typical Wiring Diagram of RES Project through MMC-HVDC Transmission

B. Fault Characteristics on the MMC-HVDC Converter Side

In order to provide voltage and frequency reference for RES stations, MMC-HVDC rectifier converter station adopt island control[18]. The diagram of the fault sequence network from the MMC-HVDC converter station to the line fault point is shown in Fig.2.

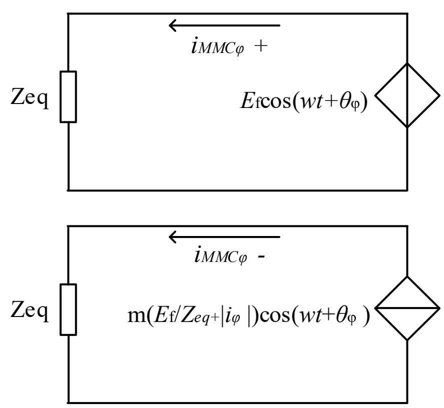

Fig.2. Fault Sequence Network Diagram

According to the positive sequence equivalent rule[13], the short-circuit current $i_{MMC\varphi}$ can be writ ten as:

$$i_{MMC\varphi} = \frac{E_f \cos(\omega t + \theta_\varphi)}{Z_{eq}} + \eta\left(\frac{E_f}{Z_{eq}} + |i_\varphi|\right) \cdot \cos(\omega^- t + \theta_{\varphi-}) \tag{2}$$

Where E_f is the equivalent voltage of the MMC-HVDC converter; Z_{eq} is the equivalent impedance and its value is related to the type of fault; θ_φ and $\theta_{\varphi-}$ are the initial phase angles of positive and negative sequences; i_φ is the short-circuit current fed from RES station; ω and ω^- are the positive and negative sequence angular frequency. η is the proportional coefficient related to the type of short-circuit. When the fault type is symmetrical fault, η =0; when the fault type is asymmetrical fault, η=1[13].

There are both positive-sequence and negative-sequence components in the short-circuit current fed from MMC-HVDC converter. Due to the control characteristics of the MMC-HVDC converter, the short-circuit current fed from inverter of RES station will also be reflected in the current from MMC-HVDC converter side[9].

when a fault occurs, the RES station presents a controlled current source and the fault current amplitude is related to the command reference value of the inverter control loop. The MMC-HVDC converter station is characterized by a controlled voltage source and the current sequence components is related to the fault type.

Different from the conventional synchronous generator system, there is a difference on the fault current characteristics between RES side and MMC-HVDC side. The following is an analysis for the adaptability of protection based on the principle of conventional AC line protection.

III. Analysis of Conventional Line Differential Protection

The conventional method of 220kV line protection adopts differential current strategy. The action equation is:

$$\begin{cases} I_{\mathrm{D\Phi}} > kI_{\mathrm{R\Phi}} \\ I_{\mathrm{D\Phi}} > I_{\mathrm{set}} \end{cases} \quad \Phi = \mathrm{A,B,C} \tag{3}$$

In (3), differential current $I_{\mathrm{D\Phi}}=\left|\dot{I}_{\mathrm{M\Phi}}+\dot{I}_{\mathrm{N\Phi}}\right|$, is the magnitude of the current vector sum; Restraint current $I_{\mathrm{R\Phi}}=\left|\dot{I}_{\mathrm{M\Phi}}-\dot{I}_{\mathrm{N\Phi}}\right|$, the magnitude of the current vector difference; k is the proportional braking coefficient (a constant greater than 1); I_{set} is the fixed value of differential current; Φ is the phase, Φ=A, B, or C.

Coefficient of protection action:

$$K_{\mathrm{a}} = \frac{I_{\mathrm{D\Phi}}}{I_{\mathrm{R\Phi}}} \tag{4}$$

K_{a} can measure the degree that the differential current is greater than the braking current, reflecting the sensitivity of the protection in fault action.

Taking the phase-to-phase short-circuit fault as an example, analyze the currents i_{m} and i_{n}. The RES station side short-circuit current of phase φ is:

$$i_{\mathrm{m}} = i_{RES+} \tag{5}$$

The short-circuit current on the side of the MMC-HVDC converter station:

$$i_{\mathrm{n}} = i_{MMC+} + i_{RES-} \tag{6}$$

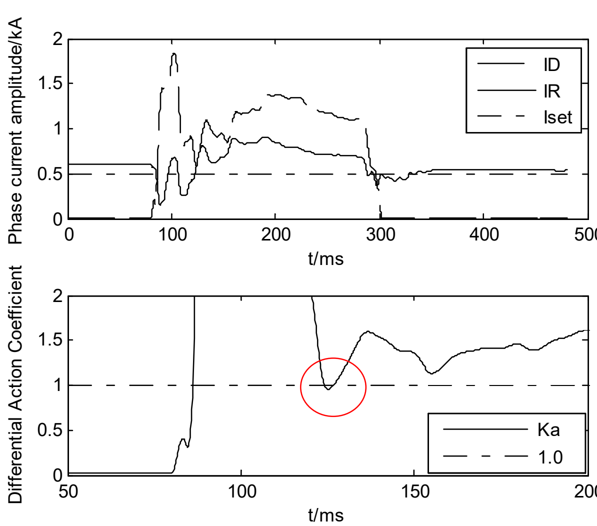

Fig.3. Differential Protection Action during Phase-to-Phase Short-circuit Fault

In (5) and (6), the composition of current sequence components is different, so there must be a phase angle difference between the short-circuit currents on both sides.

The action of the differential protection of the 220kV line phase-to-phase fault is shown in Fig.3.

It can be seen from the figure that there is a situation where the differential current is less than the restraint current during the fault phase. The protection sensitivity decreases and the protection may return after the action. In some severe case, it may refuse to operate.

IV. Differential Protection of Waveform Metrics Based on DTW

In this paper, a new method of differential protection based on DTW algorithm is proposed. The DTW is an algorithm that can measure the degree of waveform similarity of two time series.

A. *Protection principle*

For two sets of time series $X(m)$ and $Y(n)$, construct a distance matrix d with m rows and n columns:

$$d(\mathrm{i,j}) = \left\| X_{\mathrm{i}} - Y_{\mathrm{j}} \right\|^2 \tag{7}$$

In (7), $\mathrm{i} = 1,2,3,\cdots,m$; $\mathrm{j} = 1,2,3,\cdots,n$ 。

Calculate the cumulative distance of the distance matrix and get the cumulative distance matrix D:

$$D(\mathrm{i,j}) = \min\left\{D(\mathrm{i}-1,\mathrm{j}-1), D(\mathrm{i}-1,\mathrm{j}), D(\mathrm{i},\mathrm{j}-1)\right\} + d(X_{\mathrm{i}}, Y_{\mathrm{j}}) \tag{8}$$

The value of the last element D(m , n) in matrix D, which is the shortest cumulative distance of the two sets of time series:

$$D_{\min} = D(\mathrm{n,m}) \tag{9}$$

$D_{\min}$ can reflect the degree of similarity of the waveforms of the time series $X(m)$ and $Y(n)$.

Through Fourier Transform or other algorithms, the power frequency amplitude of the short-circuit current can be extracted. And the sampled values $i_{\mathrm{m}}(k)$ and $i_{\mathrm{n}}(k)$ of the current discrete quantities can be obtained. For external faults, the through current flows on both sides and the two are equal in magnitude and opposite in direction. At this time, $i_{\mathrm{m}}(k) \approx i_{\mathrm{n}}(k)$, according to (9). At this point, there is $D_{\min} \approx 0$. For internal faults, the two currents are unequal and in the same direction. At this point, there is $D_{\min} >> 0$.

The shortest cumulative distance can characterize the waveform similarity of the short-circuit current on both sides. For internal faults, the waveform similarity is high, and the shortest cumulative distance is close to zero; For external faults, the waveform similarity is low, and the shortest cumulative distance is far greater than zero. A value of waveform similarity close to zero can be selected to distinguish faults inside and outside the line. Based on this principle, the short-circuit current waveform similarity measured by DTW algorithm can be constructed for a new differential protection.

B. protection criterion

It is stipulated that the RES station side of the 220kV line is the *M* side and the MMC-HVDC converter station side is the *N* side. The discrete quantities of the $\Phi(\Phi$=A, B, C) phase current measured by the current transformers are $i_{m\Phi}(k)$ and $i_{n\Phi}(k)$ respectively, then the elements of the distance matrix *d* are:

$$d_{\Phi}(\mathrm{i},\mathrm{j})=\left\|i_{m\Phi}(\mathrm{i})-i_{n\Phi}(\mathrm{i})_{\mathrm{j}}\right\|^{2} \tag{10}$$

In (10), $\mathrm{i},\mathrm{j}=1,2,3,\cdots,k$.

Calculate the cumulative distance matrix:

$$\begin{aligned}D_{\Phi}(\mathrm{i},\mathrm{j})&=\min\{D_{\Phi}(\mathrm{i}-1,\mathrm{j}-1),D_{\Phi}(\mathrm{i}-1,\mathrm{j}),D_{\Phi}(\mathrm{i},\mathrm{j}-1)\}\\&+d_{\Phi}(i_{m}(\mathrm{i}),i_{n}(\mathrm{j}))\end{aligned} \tag{11}$$

Calculate the shortest cumulative distance for short-circuit current:

$$D_{\min}=D_{\Phi}(k,k) \tag{12}$$

The action criterion for protection is:

$$D_{\min}>D_{\mathrm{set}} \tag{13}$$

D_{set} is the setting value of the protection. Combined with the simulation results, D_{set} is set to 0.5 in order to leave sufficient margin.

V. SIMULATION AND VERIFICATION

The ADPSS simulation platform is used to build the MMC-HVDC transmission system model and RES station shown in Fig.1.The RES station includes a total of 25 4MW direct-drive wind turbines and a total of 500 0.2MW PVs. The RES station is connected to the external power grid through a 35kV/220kV step-up transformer; the 220kV transmission line is 35km long; The detailed parameters are shown in TABLE 1.

TABLE 1 DETAILED PARAMETERS OF THE SIMULATION MODEL[19]

Model	Parameter	Value
Direct-drive Wind Turbine / PV Inverter	Rated Power	4MW/0.2MW
	Rated Voltage	0.69/35kV
	Type	Wind Turbine： MingYang, MySE4.0/(YDR-F4000-G01) PV： HUAWEI, SUN2000-196KTL-H0
	Control Strategy	Suppressing Negative Sequence Current Control
MMC-HVDC Inverter	Rated Voltage	±500/kV
	Rectifier Converter	Island Control
	Inverter Converter	Constant DC Voltage Control and Constant Reactive Power Control
	Maximum Current	4 kA
	Voltage Limit	5.2kV/4.5kV
	Rated Current	2 kA

The current sampling frequency is 5 kHz. Set F1, F2, F3, F4, F5 faults on the line shown in Fig.4.

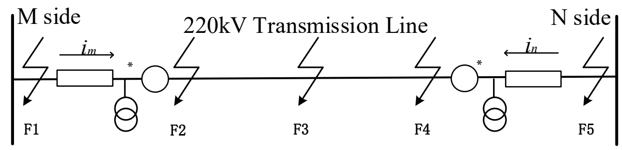

Fig.4 Line Fault Location

The calculation results of the phase-to-phase short-circuit faults of faults F3 and F1 are shown in Fig.5 and Fig.6.

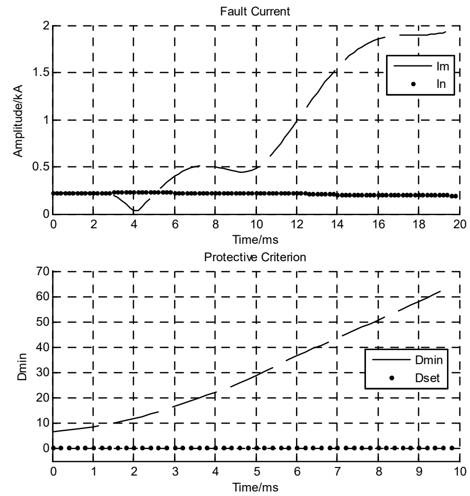

Fig.5 Short-circuit Current and Protection Calculation Results of F3 Phase-to-phase Short-circuit Fault

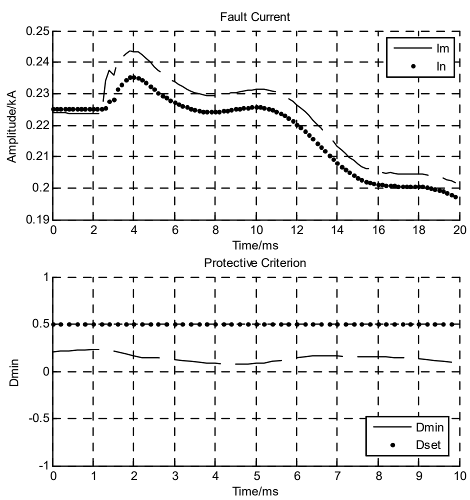

Fig.6 Short-circuit Current and Protection Calculation Results of F1 Phase-to-phase Short-circuit Fault

As can be seen from Fig.5 and Fig.6, for the internal fault F3, the protection criterion is satisfied; for the external fault F1, the protection criterion is not satisfied and the protection does not act.

The simulated and calculated protection action results of all faults are shown in TABLE 2.

From the results in TABLE 2, the proposed protection method can correctly identify all types of internal faults on the line, and reliably does not act in case of external faults.

TABLE 2 RESULTS OF SIMULATIONS AND CALCULATIONS

Fault Location	The Fault	Fault Type	D_{min}	Protection
Internal Faults	F2	Single-phase-to-ground fault	6.15	correct action
		Phase-to-phase fault	4.1	correct action
		Phase-to-phase ground fault	1.04	correct action
		Three-phase fault	3.14	correct action
	F3	Single-phase-to-ground fault	8.24	correct action
		Phase-to-phase fault	3.36	correct action
		Phase-to-phase ground fault	7.76	correct action
		Three-phase fault	6.7	correct action
	F4	Single-phase-to-ground fault	5.01	correct action
		Phase-to-phase fault	2.8	correct action
		Phase-to-phase ground fault	4.93	correct action
		Three-phase fault	5.7	correct action
External Faults	F1	Single-phase-to-ground fault	0.224	no action
		Phase-to-phase fault	0.224	no action
		Phase-to-phase ground fault	0.179	no action
		Three-phase fault	0.319	no action
	F5	Single-phase-to-ground fault	0.068	no action
		Phase-to-phase fault	0.041	no action
		Phase-to-phase ground fault	0.064	no action
		Three-phase fault	0.079	no action

VI. CONCLUSION

1) There are power electronic controlled power sources on both sides of the AC transmission lines of RES power through MMC-HVDC. The sensitivity performance of the conventional differential protection is reduced;

2) The distance matrix is constructed by calculating the Euclidean distance of the currents and then the shortest cumulative distance is obtained to characterize the waveform similarity. The protection criterion can be constructed;

3) The proposed protection method can reliably and correctly identify various types of internal and external faults.

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