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Waveform-Similarity-Based Protection Scheme for AC Transmission Lines of MMC-HVDC System with Offshore Wind Farms

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Abstract: The modular multilevel converter (MMC) has become a very promising technology for long-distance and large-capacity transmission of offshore wind power. However, both sides of the AC transmission line at the sending end are controllable electronic power devices, resulting in difficulty in fault identification and inapplicability of traditional differential protection schemes. In order to solve this problem, a wave-similarity-based protection scheme is proposed for AC transmission line faults. Firstly, the symmetrical and asymmetrical fault current characteristics of the double-fed induction generator (DFIG) and MMC are studied, indicating that the fault current characteristics are obviously different from the synchronous units. Secondly, the wave-similarity-based protection scheme is proposed based on the different wave forms of the fault currents of the MMC and DFIG. When the similarity coefficient is less than the margin coefficient, there is a fault in this phase. Moreover, the proposed wave-similarity-based protection scheme can identify all types of short-circuit faults correctly and is not affected by the transition resistance. Finally, simulations of an MMC-HVDC system with offshore wind farms are conducted to validate the effectiveness and correctness of the proposed protection scheme.

Keywords: offshore wind farm; MMC-HVDC; wave similarity; protection scheme; AC fault



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1. Introduction

Offshore wind energy has advantages such as being rich in resources, renewable, and suitable for large-scale development, so offshore wind power has a great prospect in the future [1–3]. Connecting offshore wind farms to AC systems through voltage-source-converter-based high-voltage DC system (VSC-HVDC) can achieve AC/DC isolation, making offshore wind farms unaffected by the voltage fluctuations of the AC power system, enhancing the fault ride through the capability of wind farms [4–6]. Therefore, VSC-HVDC with offshore wind farms has become a popular grid access mode (see, for example, the “Rudong” offshore wind farm project in China) [7,8].

Compared with the two-level and three-level VSC topologies, the modular multilevel converter (MMC) has the advantages of strong scalability, high degree of modularization, good power quality, low switching frequency, and so on, and it has become the preferred scheme for HVDC systems [9–11]. In addition, double-fed induction generators (DFIGs) are the main types of wind power generation at present due to their high technical maturity and good economy.

When a short-circuit fault occurs, due to the input of crowbar resistance, the rotor speed of DFIG is different from the synchronous speed. Its fault current not only includes 50 Hz components and damping DC components, but also includes damping frequency components of 35 to 65 Hz. Therefore, the fault current characteristics of DFIG are obviously different from traditional synchronous units [12,13]. Under an asymmetrical fault, the positive and negative sequence impedances of DFIG are not equal, and high-order

harmonics are generated, so the traditional pilot protection based on synchronous units cannot be fully applied. It is pointed out in [14] that due to the frequency shift of the DFIG, the pilot protection of AC lines based on synchronous units will produce the phenomena of rejection and maloperation. To solve this problem, the authors of [15] propose a novel protection scheme for the comparison of current amplitude difference. The authors of [16] adopt the least square method to identify the fault line parameters and solve the problem of distance protection failure when the DFIG is grounded through high resistance. The authors of [17] propose using the magnitude of the comprehensive impedance modulus to distinguish internal and external faults. However, the above protection is still designed based on synchronous units. When a short-circuit fault occurs, the rotation frequency component of the fault current is far greater than the power frequency component, and the new protection will still be affected by the frequency offset.

When a fault occurs on the AC side of the sending-end MMC, due to the influence of the control strategy, its short circuit current is also significantly different from that of the synchronous units [18]. The authors of [19] propose a Euler-Lagrange-model-based MMC controller, which improves the dynamic control performance of the MMC. On this basis, the authors of [20] propose a positive and negative sequence current control based on the Euler-Lagrange model for negative sequence current caused by unbalanced grid voltage or asymmetric fault of the AC system.

Therefore, the fault currents of both DFIGs and MMCs cause the performance of the traditional pilot protection based on synchronous units to be inapplicable. The main contributions of this paper can be summarized as follows:

- (1) The analytical expressions of the fault currents of DFIG and MMC are analyzed.
- (2) The adaptability of the traditional differential protection to the AC transmission line at the sending end is verified, and it is found that traditional differential protection cannot accurately identify the faults.
- (3) According to the waveform difference of fault currents on both sides of the fault point, a new principle of pilot protection based on waveform similarity is proposed, and all types of short-circuit faults can be identified correctly.

The rest of this paper is organized as follows. In Section 2, the fault current characteristics of the AC line faults at the sending end are studied. The novel waveform-similarity-based protection scheme is proposed in Section 3. Simulations of a DFIG wind farm via MMC-HVDC system under different faults have been conducted in PSCAD/EMTDC to validate the effectiveness of the proposed protection scheme in Section 4. Finally, conclusions and future work are provided in Section 5.

2. Fault Current Characteristics

The topology of the MMC-HVDC with offshore wind farms is shown in Figure 1. The wind farms are collected and boosted through AC lines, and then connected to the onshore power grid through the MMC-HVDC system. MMC1 works at the v_f control mode, providing a stable AC voltage for integration of DFIGs. In addition, MMC2 works at the DC voltage control mode, making the DC voltage fluctuate within a limited range no matter what the transmission power is.

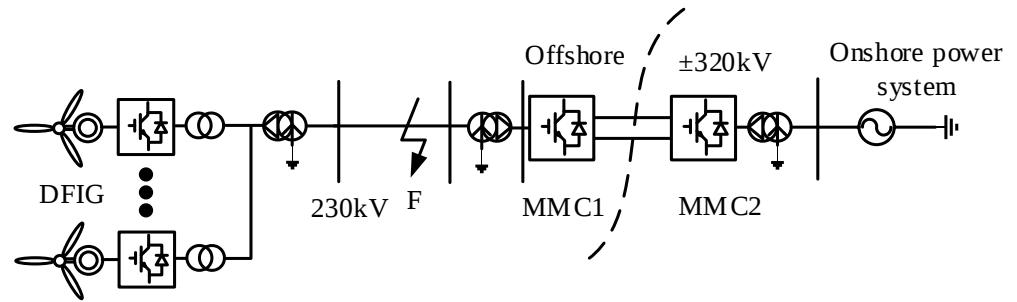


Figure 1. Topology of MMC-HVDC with offshore wind farms.

2.1. Fault Current Characteristics of DFIG

(1) Three-phase short-circuit

When a three-phase short circuit fault occurs at the DFIG terminal, the voltages before and after the fault are u_1 and ku_1 , respectively. In addition, $0 \leq k < 1$. Ignoring the stator resistance, the stator flux before the fault is

$$\psi'_s = u_1 e^{j(\omega_s t + \theta)} / j\omega_s \quad (1)$$

where ψ'_s is the stator flux before the fault, u_1 is the AC voltage of the DFIG terminal, ω_s is the speed of the stator, and θ is the initial phase angle.

Similarly, the stator flux after the fault is

$$\psi''_s = ku_1 e^{j(\omega_s t + \theta)} / j\omega_s \quad (2)$$

where ψ''_s is the stator flux after the fault.

According to the principle of flux conservation, the stator flux during the fault is

$$\psi_{s1} = \frac{ku_1 e^{j(\omega_s t + \theta)}}{j\omega_s} + \frac{(1-k)u_1 e^{j(\omega_s t_0 + \theta)}}{j\omega_s} e^{-\frac{t-t_0}{T_s}} \quad (3)$$

where ψ_{s1} is the stator flux during the fault, t_0 is the fault time, and T_s is the stator damping time constant.

The rotor flux before the fault is

$$\psi'_r = u_1 e^{j\omega_s t} L_m / j\omega_s L_s \quad (4)$$

where ψ'_r is the rotor flux before the fault, L_m is the mutual inductance of the stator and the rotor, and L_s is the stator inductance.

After the fault, the crowbar resistance is switched on instantaneously, and the rotor voltage u_r drops to 0. The rotor flux after the fault is

$$\psi''_r = \frac{ku_1 e^{j(\omega_s t + \theta)}}{j\omega_s \left(\frac{L_s}{L_m} + \frac{j(\omega_s - \omega_r)}{(R_r + R_{cb})L_m} (L_s L_r - L_m^2) \right)} \quad (5)$$

where ψ''_r is the rotor flux after the fault, and L_r is the rotor inductance.

According to the principle of flux conservation, the rotor flux during the fault is

$$\psi_{r1} = \psi''_r + (\psi'_r(t_0) - \psi''_r(t_0)) e^{j\omega_r t} e^{-\frac{t-t_0}{T_r}} \quad (6)$$

where ψ_{r1} is the rotor flux during the fault, t_0 is the fault time, and T_r is the rotor damping time constant.

Taking (3) and (6) into consideration, the fault current of DFIG during the fault is

$$i_{s1} = \frac{L_r \psi_{s1} - L_m \psi_{r1}}{L_s L_r - L_m^2} \quad (7)$$

where i_{s1} is the fault current of DFIG during the fault.

(2) Asymmetrical fault

When an asymmetric short circuit fault occurs at the DFIG terminal, its port voltage is

$$u_s = u_1 e^{j(\omega_s t + \theta)} + u_2 e^{j(-\omega_s t + \theta')} \quad (8)$$

where u_2 is the negative sequence voltage of DFIG.

The initial flux of the negative sequence stator and the rotor is 0. Since the stator flux cannot change suddenly, the stator flux generated by the negative sequence voltage is

$$\psi_{s2} = \frac{u_2 e^{j(-\omega_s t + \theta')}}{-j\omega_s} + \frac{u_2 e^{j(-\omega_s t_0 + \theta')}}{j\omega_s} e^{\frac{-(t-t_0)}{T_s}} \quad (9)$$

According to the principle of flux conservation, the rotor flux linkage generated by the negative sequence voltage is

$$\psi_{r2} = \psi_r''' - \psi_r'''(t_0) e^{-\frac{t-t_0}{T_r}} e^{j\omega_r t} \quad (10)$$

The negative sequence stator fault current is

$$i_{s2} = \frac{L_r \psi_{s2} - L_m \psi_{r2}}{L_s L_r - L_m^2} \quad (11)$$

According to (7) and (11), the fault current of DFIG during the asymmetrical fault is

$$i_s = i_{s1} + i_{s2} \quad (12)$$

2.2. Fault Current Characteristics of MMC at the Sending End

(1) Three-phase short-circuit

The inertia of the MMC is small, and the response time of the controller is between several milliseconds and more than ten milliseconds. After the fault occurs and before the controller responds, the fault current of the MMC is similar to the fault current of the conventional unit, but after the controller works, the fault current characteristics of the MMC will change.

When the fault occurs, the AC voltage decreases. Then, the order of the d -component of the current is

$$i_d^* = k_{pp}(U_{sd}^* - U_{sd}) + k_{pi} \int (U_{sd}^* - U_{sd}) dt \quad (13)$$

where i_d^* is the order of the d -component of the current, U_{sd}^* is order of the d -component of the AC voltage, U_{sd} is the measured d -component of the AC voltage, k_{pp} is the scale coefficient, and k_{pi} is the integral coefficient.

As U_{sd}^* remains unchanged, when the fault occurs, the output of the outer loop i_d^* will increase. Finally, $|i_d^*| = i_{d\max}^*$, and $i_{d\max}^*$ is the maximum limiting value of the d - outer loop. Similarly, $|i_q^*| = i_{q\max}^*$, and $i_{q\max}^*$ is the maximum limiting value of the q - outer loop.

Therefore, the positive sequence network of the MMC is equivalent to an AC current source affected by both d -axis current and q -axis current.

(2) Asymmetrical fault

When an asymmetric fault occurs, the AC bus voltage of the MMC will no longer be balanced, resulting in negative sequence components. In order to prevent the superposition

of the negative sequence current and positive sequence current from exceeding the upper safety limit, the MMC generally adopts the negative sequence current suppression strategy. The basic principle of negative sequence current suppression is to decouple the inner loop current control system into an independent positive sequence control system and negative sequence control system.

To ensure that no negative sequence current is generated in the system under any circumstances, the reference values of negative sequence active current and reactive current are generally set to 0. After the negative sequence current suppression strategy is adopted, the negative sequence loop current is basically suppressed to 0, but the negative sequence voltage still exists. Therefore, for the positive and negative sequence decoupling control mode with negative sequence suppression strategy, the equivalent impedance of the negative sequence loop of the converter station is large when the AC line of the MMC has an asymmetric fault.

Based on the above analysis of the fault characteristics of MMC and DFIG, it can be seen that there is a huge difference between the amplitude and phase angle of the short-circuit current injected by the MMC and DFIG to the fault point, which means the waveform difference is obvious. Therefore, Tanimoto similarity can be used to quantitatively measure this waveform difference and serve as the criterion for the action of pilot protection.

3. Waveform-Similarity-Based Protection Scheme

When the external fault of the AC transmission line at the sending end occurs, the fault currents provided by the DFIG and the MMC to the fault point are equal in size and opposite in direction, and the waveform is basically the same. However, when the internal fault occurs, the waveform of the fault currents provided by DFIG and MMC are obviously different. Tanimoto similarity is used to quantitatively measure this waveform difference. The proposed protection can correctly distinguish internal and external faults and act quickly and effectively in the case of internal fault of the AC transmission line.

At the same time, this waveform-similarity-based protection does not need all of the power frequency cycle sampling data, which can effectively avoid the problem that the pilot protection cannot operate correctly and effectively due to fast blocking of the MMC.

3.1. Principle of Tanimoto Similarity Theory

The protection devices at both ends of the AC transmission line conduct discrete sampling of each phase current to form two groups of one-dimensional arrays, respectively.

Note that $x = \{x_1, x_2, \dots, x_n\}$ and $y = \{y_1, y_2, \dots, y_n\}$ represent these two groups of one-dimensional data, where n is the number of sampling points in the sampling period, and the calculation formula for measuring the difference between these two groups of one-dimensional arrays with Tanimoto similarity is [21]

$$r(x, y) = \frac{\sum_{k=1}^n |x_k| \cdot |y_k|}{\sum_{k=1}^n x_k^2 + \sum_{k=1}^n y_k^2 - \sum_{k=1}^n |x_k| \cdot |y_k|} \quad (14)$$

According to the inequality principle, the value range of $r(x, y)$ is $[0, 1]$. If $x = y$, then $r(x, y) = 1$, which indicates that the two groups of waveforms are identical and the correlation is the strongest, but this phenomenon will not happen in the AC transmission line faults. If $x = -y$, then $r(x, y) = 1$, indicating that the two groups of waveforms have the same size, opposite direction, and the strongest negative correlation, which means the external fault occurs. When the value $r(x, y)$ is less than 1, it indicates that there is difference between the two groups of data, and the correlation is weak, which means the internal fault of the protection line occurs.

3.2. Waveform-Similarity-Based Protection Scheme

When the internal fault occurs, the MMC at the sending end will produce a low-voltage overcurrent phenomenon. To prevent the MMC from being damaged by overcurrent, it may be blocked within 5–10 ms. According to this, the sampling period of the Tanimoto similarity protection algorithm can be set as 10 ms, and the discrete current sampling frequency is set as 2.5 kHz. In this way, 25 data points can be sampled in a cycle, and the data is sufficient. When an external fault occurs, the current at both ends of the line is the same in size and opposite in direction, and the Tanimoto similarity calculation value is 1. When the line has an internal fault, the current waveforms at both ends of the line are obviously different, and the Tanimoto similarity calculation value is less than 1 and close to 0.

For the proposed protection scheme, the sampling data error at both ends mainly comes from synchronization error, CT transmission error, and amplitude error. The error coefficient is determined as 0.95, the margin coefficient is determined as 0.95, the protection setting value is $r(x, y)_{set} = 1 \times 0.95 \times 0.95 = 0.9025$, and the protection action condition is

$$r(x, y) < 0.9025 \quad (15)$$

The steps of the proposed waveform similarity protection scheme are

- (1) The current of each phase on both sides of the line shall be sampled with a sampling frequency of 2.5 kHz and a sampling period of 5 ms, and the Tanimoto similarity shall be calculated according to Equation (14).
- (2) Equation (15) is used as the criterion to judge the protection action. When the calculated Tanimoto similarity of a phase is less than 0.9025, it is a fault phase. Then, phase protection acts. When the calculated value is always greater than 0.9025, it is a non-fault phase.
- (3) If the calculated value of three-phase Tanimoto similarity is greater than 0.9025, it means that the system operates normally or the external fault of the protection line occurs.

4. Simulation Studies

Simulations of a DFIG wind farm via MMC-HVDC system under different types of AC line have been conducted in PSCAD/EMTDC to validate the effectiveness of the proposed waveform-similarity-based protection scheme. The topology is shown in Figure 1. The capacity of a DFIG is 5 MW, and the wind farm consists of 190 DFIGs. In addition, the parameters of the DFIG are shown in Table 1, and the parameters of the MMC are shown in Table 2. The AC line is 50 km, the positive sequence reactance is $0.284 + j0.824 \Omega/\text{km}$, the zero sequence reactance is $0.0766 + j0.338 \Omega/\text{km}$, and the positive sequence and zero sequence capacitors are 8.6 nF/km and 6.1 nF/km, respectively.

Table 1. Parameters of the MMC-HVDC system with an offshore wind farm.

Model Name	Parameter Name	Value
MMC	Rated capacity/MW	950
	Rated AC voltage/kV	230
	Rated DC voltage/kV	± 320
	DC capacitor of a sub-module/mF	2.8
	No. of the sub-module of one bridge	160
DFIG	Rated capacity/MW	5
	Rated voltage/kV	6.9
	Stator resistance	0.0579 p.u.
	Rotor resistance	0.00607 p.u.
	Stator leakage reactance	0.1545 p.u.
	Rotor leakage reactance	0.11 p.u.
	Mutual reactance	4.5 p.u.

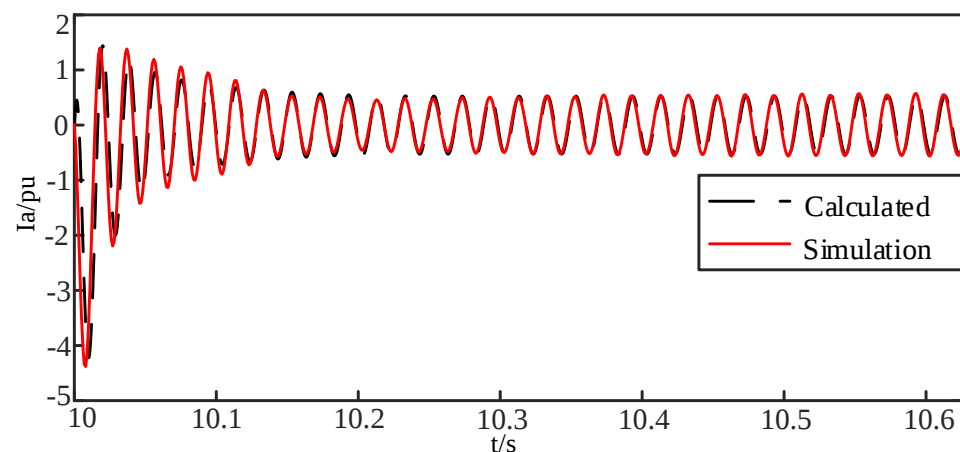
Table 2. Similarity coefficient under different fault types and transition resistances.

Fault Types	Transition Resistances/ Ω	Similarity Coefficient Value		
		Phase A	Phase B	Phase C
ABG	20	0.432	0.415	0.994
	60	0.735	0.682	0.995
	100	0.852	0.847	0.997
AB	20	0.625	0.184	0.993
	60	0.702	0.572	0.995
	100	0.805	0.732	0.996
ABC	20	0.505	0.503	0.502
	60	0.701	0.712	0.703
	100	0.852	0.854	0.801

4.1. Fault Current Characteristics of MMC and DFIG

Assume a three-phase short-circuit occurs at the point 20 km from the sending MMC at $t = 10$ s, and the fault duration is 0.625 s.

The terminal voltage of the DFIG drops to 0.23 pu, and the comparison between the waveform is calculated by Equation (12). The simulation waveform of the stator short-circuit current of a single DFIG is shown in Figure 2.

**Figure 2.** Transient current characteristics of DFIG (Phase A).

It can be seen from Figure 2 that the short-circuit current sent by DFIG is obviously different from that of the synchronous unit during the short-circuit fault. The transfer frequency component of the DFIG short-circuit current accounts for a large proportion, and its damping time constant is large, so the current damping process is slower than that of the synchronous unit.

The simulation result of the fault current of the sending-end MMC is shown in Figure 3. It can be seen that the sending-end MMC can be completely equivalent to a controlled current source with an amplitude of 1 p.u. during fault due to the low-voltage current-limiting control strategy.

4.2. Waveform-Similarity-Based Protection Scheme

Traditional differential protection is applied to the AC transmission line at the sending end. The ratio of differential protection action current to braking current is shown in Figure 4. The braking coefficient of general differential protection is set to 0.8. It can be seen from Figure 4 that traditional differential protection may not act before the sending-end MMC is blocked, resulting in incorrect action of the protection.

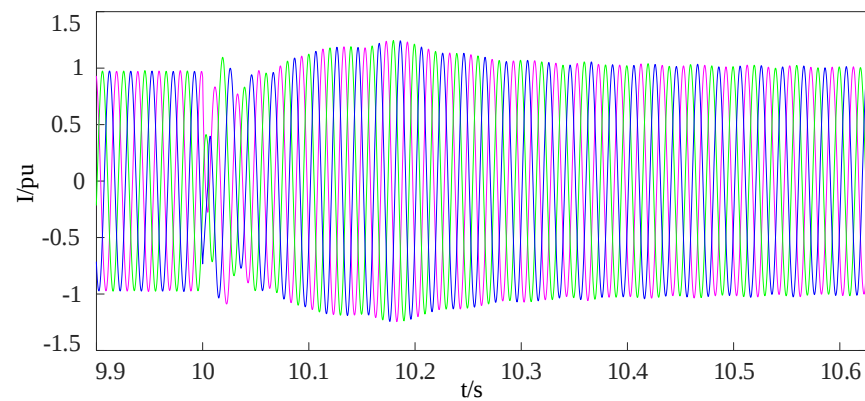


Figure 3. The fault currents of MMC (the red, blue, and green lines denote the currents of phase A, Phase B, and Phase C, respectively).

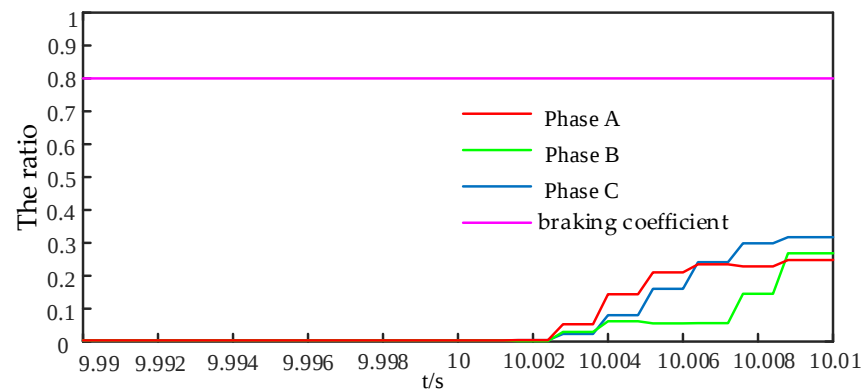


Figure 4. Performance of traditional differential protection for three-phase short circuit.

The simulation results of the proposed protection scheme under different types of faults are shown in Figure 5.

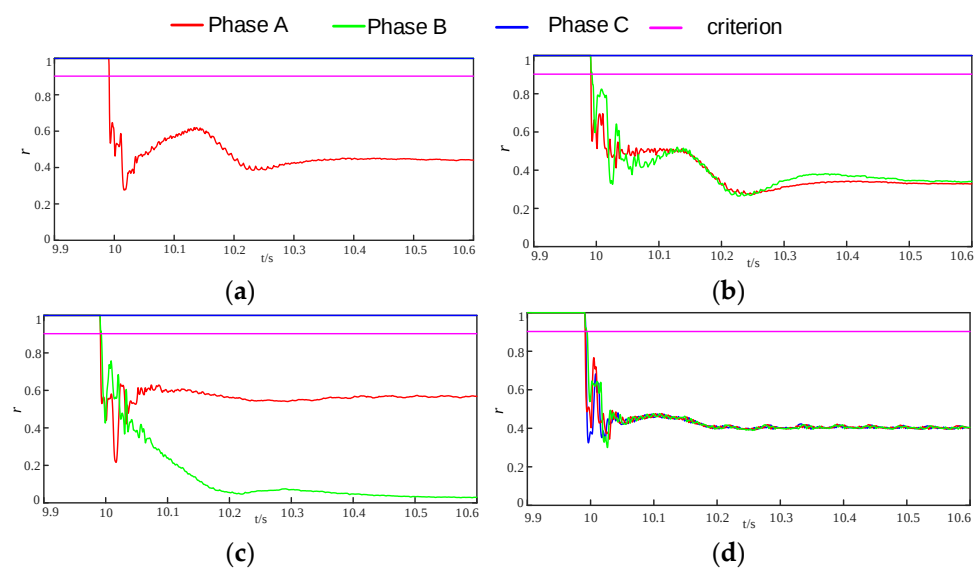


Figure 5. Performance of the proposed protection scheme under different types of faults: (a) single-phase grounding (phase A); (b) phase-to-phase grounding (phase A and B); (c) phase-to-phase short circuit (phase A and B); (d) three-phase short-circuit.

It can be seen from Figure 5 that under different types of faults, the waveform-similarity-based protection scheme can correctly and effectively act.

4.3. Influence of the Transition Resistance on the Proposed Protection

There may be some transition resistances in the short-circuit fault. The influence of the transition resistance on the proposed protection performance must be considered. The maximum transition resistance of 220 kV system is about 100 Ω . The calculation results of the similarity coefficients of different types of faults with different transition resistances (20 Ω , 60 Ω , 100 Ω) are shown in Table 1.

It can be seen from Table 2 that the waveform similarity coefficient tends to increase with the increase of the transition resistance, but the protection still has good performance and is still applicable in the case of high-resistance fault.

5. Conclusions

In this paper, the short-circuit current characteristics of DFIG and MMC are analyzed in detail, and it is concluded that the current amplitude and phase angle of the DFIG and MMC at MMC are significantly different from those of the synchronous unit, which indicates that traditional pilot protection may not be fully applied to AC transmission lines' protection of the sending end of MMC-HVDC. Therefore, a waveform-similarity-based protection scheme is proposed. The theoretical and the simulation results show that the proposed protection can act quickly and effectively under various types of short-circuit faults and is not affected by the size of transition resistance.

The engineering application of the proposed waveform-similarity-based protection scheme should be considered, and the location of the fault should be studied in the further work.

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