New Principle of Pilot Protection Based on Kendall's Rank Correlation Coefficient

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Abstract. Affected by the control strategy after MMC failure, the fault current on the converter side of the AC line interconnected with the MMC is significantly different from the fault characteristics of the traditional power supply in amplitude and phase. The new fault current characteristics lead to the inapplicability of the traditional longitudinal current phase differential protection. In order to solve the problem of the applicability of relay protection, a new principle of longitudinal protection based on Kendall's rank correlation coefficient is proposed. After the AC line fails, the Kendall grade correlation coefficient of the calculated current on both sides is calculated to distinguish the internal and external faults. Simulations are carried out on the RTDS platform, and the results show that the proposed protection principle can reliably distinguish between internal and external faults and has the ability to withstand transition resistance under various control reference values.

1. Introduction
The MMC-based flexible DC transmission technology can solve the risk of commutation failure in conventional DC. At the same time, it has received widespread attention due to its more flexible control methods, less reactive power requirements and no need for filtering\textsuperscript{[1]}. The pilot protection of the AC line interconnected with MMC is affected by the inverter control strategy and is not applicable. Literature [2] proposed a control strategy that the AC line interconnected with the MMC is suppressed by the negative sequence by the MMC. There is a random error in the phase angle difference between the negative sequence current and the negative sequence voltage, which causes the direction indication of the negative sequence directional element to be unclear, so Longitudinal negative sequence protection will appear inapplicable. Literature [3] analyzed the phase characteristics of the fault current sent by the MMC, and got the conclusion that the pilot current phase differential protection may have a malfunction. Literature [4] analyzed the longitudinal current differential protection of the AC line interconnected with the MMC. Affected by the control parameters after the MMC failure, the protection has the risk of refusal to operate. Literature [5-6] proposes to reapply the longitudinal negative sequence directional protection by sending out a negative sequence current of a specific phase and amplitude through the MMC when the AC line fails. However, the negative sequence current will cause a certain degree of damage to power electronic devices.
This paper according to the phase characteristics of the fault current on the synchronous grid side and the converter side of the fault line, a new principle of pilot protection based on Kendall's rank correlation coefficient is proposed. And the simulation on the RTDS simulation platform verifies that the protection principle can accurately reflect the fault under different fault locations and different transition resistances.

2. The control strategy of MMC

As shown in Figure 1, MMC1 is interconnected with the synchronous power grid 1 through a connection line MN, MMC2 is interconnected with the synchronous power grid 2, and MMC3 is interconnected with the wind farm. Among them, MMC1 uses constant DC voltage control and constant reactive power control; MMC2 uses constant active power control and constant reactive power control; MMC3 uses constant AC voltage amplitude and constant AC voltage frequency control. \( I_M \) and \( I_N \) are respectively the current flowing to the line from the converter side bus M of the tie line MN and the synchronous grid side bus N. k is the fault point of the AC line.

Figure 1. Three-terminal MMC topology diagram

When an asymmetrical fault occurs on the transmission line interconnected with MMC1, no zero sequence current flows through the delta side of the converter transformer, only positive sequence current and negative sequence current components exist. The negative sequence component may cause the converter station to be quickly locked, and in severe cases may also cause damage to the power components. Therefore, filtering the negative sequence current is very necessary for the safety of the converter station. In this regard, current engineering often uses control strategies to limit the current amplitude and suppress negative sequence current. The current amplitude is generally limited to 1.1-1.2 times the rated current.

3. New protection principle based on Kendall’s rank correlation coefficient

3.1. Introduction to Kendall’s rank correlation coefficient

The Kendall’s rank correlation coefficient is a method used to measure the degree of correlation between two phasors. If the two phasors are completely opposite, the Kendall rank correlation coefficient is -1. If the two phasors are exactly the same, then the Kendall rank The correlation coefficient is 1. In other cases, it changes between -1 and 1, and the specific ideas are as follows.

The two phasors to be compared \( x = \{x_1,x_2,......,x_n\} \), \( y = \{y_1,y_2,......,y_n\} \), in ascending or descending order of \( x_i \) and \( x_j \) and \( y_i \) and \( y_j \). The corresponding sequence is arranged in the same arrangement, and the phasors \( a = \{a_1,a_2,......,a_n\} \), \( b = \{b_1,b_2,......,b_n\} \), and then calculate the same ordinal number \( P \) of the phasor \( b \), and substitute the same ordinal number \( P \) and the number of phasor points \( n \) into the Kendall rank correlation coefficient calculation formula:

\[
k = \frac{4P}{n(n-1)} - 1
\]  

(1)
Therefore, the Kendall level correlation coefficient of the phasor formed by the two waveform sample values is related to the order of the magnitude of the vector formed by the sample values.

3.2. New principles of pilot protection

The fault current on the converter side of the AC line interconnected with the MMC shows power frequency characteristics and the phase is controlled. Therefore, under a certain control parameter, the currents on both sides of the fault phase may show completely opposite phase characteristics. At this time, the protection principle based on the level correlation coefficient cannot accurately distinguish the fault type. After the fault, there is no negative sequence current on the converter side and the negative sequence current on the synchronous grid side is equal to the negative sequence current at the fault point. Therefore, by comparing the calculated current formed by the sum of the positive sequence component and the negative sequence component of the current on both sides of the fault line, the internal and external faults can be distinguished reliably. Then use the phase selection component to cooperate with it to determine which phase the fault phase is.

Define calculated current:

\[ I_{Jx} = I^+_x + I^-_x \]  

(2)

Where \( x \) represents one of the three phases of A, B, and C, \( I^+_x \) is the positive sequence current of phase \( x \); \( I^-_x \) is the negative sequence current of phase \( x \); \( I_{Jx} \) is the calculated current of phase \( x \).

As shown in Figure 2(a), after the AB two-phase fault occurs, the phases of the currents of the A and B phases on the synchronous grid side are opposite, and the currents on the converter side are three-phase symmetrical. The phase angle difference of the fault currents on both sides of the A phase is \( \theta_A \), and the phase B The phase angle difference of the fault current on both sides is \( \theta_B \). When the phase difference of the current on both sides of the line is 180°, the calculated Kendall level correlation coefficient will be the same as that of the non-fault phase. However, it can be seen from the vector diagram that \( \theta_A \) and \( \theta_B \) will not be 180° at the same time. Therefore, it is possible to reliably identify the fault in the area after the AC line has a fault in the area.

As shown in Figure 2(b), after the occurrence of a phase A fault, the phases of the calculated currents of the two phases B and C on the synchronous grid side are the same and are opposite to the calculated currents of the phase A. The converter side current is three-phase symmetrical, the phase angle difference of the fault current on both sides of phase A is \( \theta_A \), the phase angle difference of the fault current on both sides of phase B is \( \theta_B \), and the phase angle difference of the fault current on both sides of phase C is \( \theta_C \). It can be seen from the vector diagram that \( \theta_A \), \( \theta_B \), and \( \theta_C \) will not be 180° at the same time. Therefore, it is possible to reliably identify the fault in the area after the AC line has a fault in the area.

Literature [7] proposed a phase selection method based on voltage sequence components that can be applied to AC line faults interconnected with MMC. The phase selection process is shown in Figure 3.
After the fault, the phase selection component judges the fault phase according to the flow chart according to $U_{MA2}$, $U_{MA0}$, $\gamma_{mag}$, $\gamma_{phase}$. Among them, $U_{MA1}$, $U_{MA2}$, $U_{MA0}$ are respectively the positive, negative and zero sequence components of the bus voltage on the converter side of the faulty line. $\gamma_{mag}$ and $\gamma_{phase}$ are sequence voltage amplitude ratio and sequence voltage phase angle difference respectively:

$$\gamma_{mag} = \frac{|U_{MA0}|}{|U_{MA1}| + |U_{MA2}|}, \quad \gamma_{phase} = \frac{\arg U_{MA1}}{U_{MA2}}$$

**Figure 3. Schematic diagram of phase selection of voltage sequence components**

3.3. Threshold setting

As shown in Figure 4, the two waves form a completely negatively correlated waveform. The number corresponding to each sampling point is the order of the corresponding value of the sampling point in descending order. The phasor of waveform 1 corresponding to the sequence of sampling values is $x=\{10 \ 8 \ 6 \ 4 \ 2 \ 1 \ 3 \ 5 \ 7 \ 9 \ 11\}$, and the phasor of waveform 2 corresponding to the sequence of sampling values is $y=\{1 \ 3 \ 5 \ 7 \ 9 \ 11 \ 10 \ 8 \ 6 \ 4 \ 2\}$. Arrange the elements of the phasor x in descending order to obtain the phasor $a=\{1 \ 2 \ 3 \ 4 \ 5 \ 6 \ 7 \ 8 \ 9 \ 10 \ 11\}$, and keep the y phasor in the same order as the corresponding elements of the x phasor and y phasor. The arrangement of, the phasor $b=\{11 \ 10 \ 9 \ 8 \ 7 \ 6 \ 5 \ 4 \ 3 \ 2 \ 1\}$. At this time, the same ordinal number $P=0$ calculated from the

**Figure 4. Waveform sample value sorting diagram**
phasor b, and the Kendall rank correlation coefficient obtained by substituting into equation (1) is -1. However, in addition to the fixed order of the peaks, the order of the points with the same amplitude on both sides of the peak can also be interchanged. For example, the phasor \( y_2 \) formed by the arrangement order of the sample values corresponding to waveform 2 can also be \( c = \{11 \ 9 \ 10 \ 8 \ 7 \ 6 \ 5 \ 4 \ 3 \ 2 \ 1\} \) according to the arrangement order of the x phasor. At this time, the phasor c The same ordinal number \( P=1 \); the Kendall’s rank correlation coefficient calculated by substituting equation (1) is -0.964. In each period, the sampling point is n phasors. In this case, there are at most \( (n-2)/2 \) in a period. After swapping a pair of arrays with equal amplitudes, the error of the same ordinal number is 1. The maximum error caused by the exchange sequence of equal amplitude in a period is \( 2(n-2)/n(n-1) \). When the sampling frequency is 5kHz, the error caused by the exchange of the arrangement order due to the equal amplitude is: \( \Delta k_1 = 0.0198 \). It can be concluded that with the increase of the sampling frequency, the smaller the error caused by the sequence exchange due to the equal amplitude.

In the event of an area fault, the phasor Kendall rank correlation coefficient formed by the current sampling values on both sides will quickly move away from -1, so only consider how to set the threshold during normal operation. The main sources of error are data synchronization error and transformer transfer error. The asynchronous sampling delay on both sides of the AC line is 0.5ms, and the corresponding power frequency angle is 9°; the maximum angle error caused by the mutual inductors on both sides is 7°. After considering the angle margin, the angle error is 18°, corresponding to 1ms. When the sampling frequency is 5kHz, the sampling value of one cycle is 100.

\[
\Delta k_2 = 0.196, \quad \text{considering the safety margin of } \Delta k_3 = 0.004, \quad k_{set} = -1 + \Delta k_1 + \Delta k_2 + \Delta k_3 = -0.78
\]

The protection action condition is \( k > k_{set} \).

4. Simulation

In order to verify the performance of the new principle of longitudinal protection mentioned above, the three-terminal MMC model shown in Figure 1 was built in RTDS. The number of MMC half-bridge sub-modules is 200, DC voltage level is ±200kV, AC line length is 50km, AC voltage level is 220kV, AC voltage frequency is 50Hz, AC line positive sequence impedance is 0.076+j0.3766Ω/km, AC The zero sequence impedance of the line is 0.284+j0.824Ω/km.

Since different types of faults, different transition resistance sizes will have different effects on the fault characteristics. Take A-phase single-phase grounding fault, AB two-phase fault Type as an example for analysis. The transition resistance of a 220kV transmission line grounding fault generally does not exceed 100Ω, and the transition resistance of a phase-to-phase short-circuit generally does not exceed 20Ω. So set the transition resistance of the ground fault to 25Ω, 50Ω, 100Ω, and the transition resistance of the phase-to-phase fault to 10Ω, 20Ω respectively.

As shown in Figure 6(a), when a phase A ground fault occurs, the Kendall level correlation coefficients of the three phases are -0.1, -0.78, and -0.54 respectively, which can be judged as an area
fault; \( U_2=53kV, U_0=73kV, U_1=125kV, \gamma_{mag}=1, \gamma_{phase}=185^\circ \), the sequence voltage phase selection element is judged as a phase A single-phase grounding fault. When phase A is grounded, the protection can correctly judge the fault.

As shown in Figure 6(b), when an AB two-phase fault occurs, the Kendall level correlation coefficients of the three phases are 0.2, -0.52, -1 respectively, which can be judged as an area fault; \( U_2=90kV, U_0=0kV, \gamma_{phase}=239^\circ \), the sequence voltage phase selection element is judged to be AB two-phase fault. When the phase fails indirectly, the protection can correctly judge the failure.

As shown in Table 1, the protection can operate correctly after different types of faults occur through different transition resistances.

| Fault type | \( R_f/\Omega \) | \( k_a \) | \( k_b \) | \( k_c \) | \( U_2/kV \) | \( U_0/kV \) | \( \gamma_{mag} \) | \( \gamma_{phase}/^\circ \) | Result |
|------------|-----------------|-------------|-------------|-------------|--------------|--------------|----------------|-----------------|--------|
| AB         | 10              | 0.75        | -0.01       | -1          | 84           | 0            | 275^\circ       | \( f_{ab} \)     |        |
|            | 20              | 1           | 0.2         | -1          | 71           | 0            | 293^\circ       | \( f_{ab} \)     |        |
|            | 25              | -0.05       | -0.71       | -0.68       | 25           | 34           | <1 184^\circ    | \( f_{a} \)      |        |
|            | 50              | 0           | -0.7        | -0.64       | 25           | 34           | <1 182^\circ    | \( f_{a} \)      |        |
|            | 100             | -0.03       | -0.71       | -0.67       | 25           | 34           | <1 183^\circ    | \( f_{a} \)      |        |

**Summary**

A new principle of pilot protection based on Kendall's rank correlation coefficient is proposed, which can reliably distinguish between internal and external faults under different control reference values. At the same time, this method has a strong ability to withstand transition resistance.

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