Positive sequence pilot impedance protection of AC tie line based on MMC-HVDC system

Zhiyong Yang*, Bingyuan Yang

1 College of Electric Power, Inner Mongolia University of Technology, Hohhot, Inner Mongolia, 010051, China

*Corresponding author’s e-mail: 990445769@qq.com

Abstract. MMC-HVDC has the characteristics of limited amplitude, controlled phase angle and unequal positive and negative sequence impedance. Therefore, the fault characteristics of flexible direct system and AC power grid tie line are quite different from traditional synchronous power supply, which may affect the performance of AC power grid sudden variable protection. Therefore, a new AC protection method based on positive sequence current sudden variable impedance is proposed. The results show that when an in zone fault occurs, the direction of current sudden changes at both ends is the same, and the positive sequence impedance may approach the line impedance; When an out of area fault occurs, the current abrupt variables at both ends have opposite directions and equal sizes, and the positive sequence impedance is much greater than the line impedance. Based on the above characteristics, the criteria of fault start up and fault type are constructed. The simulation results show that the protection method can realize fault discrimination quickly and reliably.

1. Introduction

The research on fault characteristics is the premise of relay protection. Based on the positive and negative sequence decoupling control widely used in converter stations, the sequence network equivalent method for AC measurement of asymmetric faults in converter stations is given in Li [1]. Li [2] proposes that large-scale wind power is connected to the power grid through MMC-HVDC. Affected by the converter fault ride through strategy, the fault characteristics of AC side line of converter station are quite different from those of synchronous power grid, such as unequal positive and negative sequence impedance, controlled phase angle, limited amplitude, etc.

At present, with the development of power system scale and power electronic technology, the adaptability research of AC transmission line pilot protection in converter station is also being carried out. Li [3] improves the pilot directional protection criterion by using negative sequence component compensation and the phase relationship between zero negative sequence voltage and current, so that the protection scheme has better reliability and rapidity. In Li [4], the pilot protection scheme based on the current amplitude ratio on both sides is used to solve the problem of refusal of differential protection during large-scale new energy access. Li [5] proposed a current phase differential protection based on the current phase angle difference at both ends of the fault line, but the protection has the risk of refusing to operate in case of non grounding fault. The pilot protection scheme composed of similarity algorithm in Li [6] can reliably identify faults inside and outside the area and has good resistance to transition resistance. Li [7] proposed the concept of pilot impedance, but its application scenario is traditional power grid, and its adaptability in AC / DC hybrid system needs further analysis.
Based on the concept of pilot impedance, a protection scheme of positive sequence pilot impedance based on positive sequence current sudden variable is proposed; The protection principle is analyzed theoretically; The effects of different factors on the impedance amplitude of positive sequence pilot are studied; Finally, the simulation model is established through RTDS to verify the performance of the protection.

2. Analysis of system topology and fault characteristics
In order to study the adaptability of sudden variable impedance protection of flexible direct and AC system tie line L1, a system topology model as shown in Fig. 1 is built based on a three terminal flexible direct network. Among them, the permanent magnet direct drive wind field is equivalent by a single machine through RTDS interface transformer; The MMC connection transformer adopts YNd11 wiring mode; The converter station control is DQ decoupling control, voltage margin control is adopted between station domains, GSMMC1 is used as the main station, and constant DC voltage and constant reactive power control are adopted; In order to analyze the protection performance, f1 ~ f3 in the area and f4 ~ f5 outside the area are set as the places where various faults occur, and m and n are the protection installation places.

When dealing with the fault ride through problem of MMC-HVDC AC transmission line, the inverter station generally adopts the control strategy of restraining negative sequence current and the combined control of limiter to protect power electronic devices.

When a fault occurs, the general expression of fault current at M side is

$$i_m = \frac{I_m}{k_T} \cos(\omega t - \theta_k - \frac{\pi}{6}) + I_{f0} \cos(\omega t + \phi_0)$$

$$i_n = \frac{I_n}{k_T} \cos(\omega t - \theta_k - \frac{\pi}{6}) + I_{f0} \cos(\omega t + \phi_0)$$

$$i_j = \frac{I_j}{k_T} \cos(\omega t - \theta_k - \frac{\pi}{12}) + I_{f0} \cos(\omega t + \phi_0)$$

Among them, i=A, B, C; $\theta_k=0$, $\theta_k=-\theta_k=2\pi/3$; $I_m$ is MMC output current amplitude; $k_T$ is the transformation ratio of connecting transformer; $\omega$ is the rated angular frequency of the power grid; $\phi=\arctan(Q*/P*)$, $P*$ and $Q*$ are MMC active and reactive command values respectively; $I_{f0}$ is zero sequence current amplitude; $\phi_0$ is zero sequence current phase.

Therefore, Fig. 2 shows the topology diagram of each sequence network when there is a fault in the tie line L1; Fig. 3 shows the fault additional state diagram of phase a grounding fault of L1 line. Among them, “+”, “-”, “0” are the sequence components of fault information; U is voltage phasor. I is current phasor; ZN is the equivalent impedance of AC network. ZL is the impedance of L1 line, and ZT is the leakage reactance of transformer; Rf is the transition resistance, Uf is the fault point voltage, and If is the fault short-circuit current; D is the total length of the line, and l represents the location of the fault point; M, N is MMC side and grid side respectively; $\Delta$ represents the fault component of fault information.

The short-circuit current fault component provided by M side is mainly composed of zero sequence current and positive sequence current. The short-circuit current fault component of flexible DC side is
much smaller than that of power grid side; MMC fault current output characteristics are affected by many aspects (such as fault location, transition resistance, control strategy, etc.).

Figure 2. Fault three sequence network diagram in the area

(a) Positive sequence network  (b) Negative sequence network  (c) Zero sequence network

Figure 3. Additional fault diagram

(a) In zone fault  (b) Out of area fault

3. Pilot impedance protection scheme for positive sequence sudden variable

According to different control strategies, the fault sequence components contained in AC lines may be different. In order to eliminate the possible influence of negative sequence and zero sequence on protection, a pilot impedance protection based on positive sequence current sudden variable is proposed.

3.1. Definition of positive sequence pilot impedance

Define the positive sequence pilot impedance as

\[ Z_{op}^+ = \frac{\Delta U_{op}^+}{\Delta I_{op}^+} \]  \hspace{0.5cm} (2)

\[ \Delta U_{op}^+ = \Delta U_m^+ - \Delta U_n^+ \]  \hspace{0.5cm} (3)

\[ \Delta I_{op}^+ = \Delta I_m^+ + \Delta I_n^+ \]  \hspace{0.5cm} (4)

The following is a qualitative analysis of the numerical characteristics of the pilot impedance when an out of zone or in zone fault occurs on the line, ignoring the value of the fault resistance.

3.2. In zone fault

\[ |Z_{op}^+| = \left| \frac{\Delta U_{op}^+}{\Delta I_{op}^+} \right| = \left| \frac{\Delta I_m^+ - \Delta I_n^+ (D - l)}{\Delta I_m^+ + \Delta I_n^+} \right| \leq \left| \frac{\Delta I_m^+ - \Delta I_n^+}{\Delta I_m^+ + \Delta I_n^+} \right| DZ \]  \hspace{0.5cm} (5)

It can be seen from the formula that when a fault occurs in the area, no matter where the fault is located, \( |Z_{op}^+| \) is always less than \( |DZ| \). However, \( \Delta I_m^+ \ll \Delta I_n^+ \) may occur on the MMC HVDC grid tie line, which leads to that \( |Z_{op}^+| \) is approximately equal to \( |DZ| \).

3.3. Out of area fault

\[ \Delta U_{op}^+ = \Delta I_m^+ ZD = -\Delta I_n^+ ZD = \left( \Delta I_m^+ - \Delta I_n^+ \right) ZD / 2 \]  \hspace{0.5cm} (6)

\[ \Delta I_{op}^+ = 0 \]

\[ |Z_{op}^+| = \left| \frac{\Delta U_{op}^+}{\Delta I_{op}^+} \right| = \infty \gg |DZ| \]  \hspace{0.5cm} (8)

3
As shown in Eq. (6-8), when the fault occurs outside the protection area, it can be seen from Fig. 3(b) that the current fault component flows through the whole length of the line, and the currents on both sides of M and N are equal and opposite. At this time, $\Delta U_{op}^+$ is the voltage drop of the line fault component, which is not an infinitesimal value. Therefore, when a fault occurs outside the area, the pilot impedance amplitude is always much larger than the line impedance amplitude, which has obvious characteristics of out of area fault.

3.4. Pilot protection scheme

Criterion 1: $|\Delta I_{in}^+ + \Delta I_n^+| > I_{set}$

By selecting the appropriate setting value $I_{set}$ through this criterion, the fault phase can be identified without phase selection element; It can preliminarily identify faults in the area and eliminate faults outside the area and normal operation status.

Criterion 2: $|Z_{op}^+| = k |\Delta U_{op}^+ / \Delta I_{op}^+| < Z_{set}$

If criterion 2 is also true, it is determined that it is a fault in the area and the protection acts; Otherwise, it is an out of area fault, and the protection is reliable and does not act.

In order to consider the sensitivity of protection action, the setting value $Z_{set}$ of protection action can be set as $(1.5~2) |Z_D|$, which can ensure that the positive sequence pilot impedance $|Z_{op}|$ is significantly less than the setting value $Z_{set}$ in any case of fault in the area.

4. Simulation verification

In this paper, the topology model as shown in Fig. 1 is built through RTDS platform to discuss the positive sequence pilot impedance protection performance of flexible direct AC grid connection tie line L1 line. The DC system voltage level is ± 200 kV, GSMMC1 is 400 MW, and the bridge arm current rating is 1 kA; The L1 voltage level of the grid connected tie line is 220 kV, the positive sequence impedance of the transmission line is 0.076+j0.338 Ω·km$^{-1}$, the zero sequence impedance is 0.284+j0.824 Ω·km$^{-1}$, the equivalent impedance of the AC system connected on side N is 5+j7.798 Ω·km$^{-1}$, and the leakage reactance of the connecting transformer is 0.18.

4.1. Calculation results of positive sequence pilot impedance

As shown in Table (1-3), the data in the table are the maximum value of positive sequence pilot impedance simulation waveform after fault occurs at different fault locations and fault types under different transition resistance conditions. In order to avoid protection misoperation caused by interference, an information comparison link can be set for a period of time, and the maximum value information can be retained to ensure the correctness and effectiveness of data. Table (1-3) shows the amplitude of pilot positive sequence impedance in case of single-phase grounding fault, phase to phase short circuit fault and three-phase short circuit, and the impedance amplitude is Ohm (Ω).

| Fault type | AG | Transition resistance | 0 | 10 | 100 |
|------------|----|----------------------|---|----|----|
| Fault location | $|Z_{op}|$ | Action | $|Z_{op}|$ | Action | $|Z_{op}|$ | Action |
| k1 | 18.39 | √ | 21.83 | √ | 18.67 | √ |
| k2 | 16.59 | √ | 16.77 | √ | 19.73 | √ |
| k3 | 16.77 | √ | 17.08 | √ | 20.25 | √ |
| k4 | 1097 | × | 972.2 | × | 1750 | × |
| k5 | 17083.3 | × | 8958.33 | × | 11250 | × |
Table 2. Amplitude of positive sequence pilot impedance in case of phase to phase short circuit between L1 line and ab line in RTDS simulation. (I_{set}=1A; Z_{set}=2*|DZ|=34.64Ω)

| Fault type | Transition resistance | Fault location | | Action | | Action | | Action |
|------------|----------------------|----------------|-----------------|-----------------|-----------------|-----------------|
|            | Z_{op}               | Z_{op}          | Z_{op}          |                 |                 |                 |
|            |                      |                |                 |                 |                 |                 |

| k1         | 15.18                | √              | 16.45           | √               | 16.83           | √               |
| k2         | 15.82                | √              | 16.13           | √               | 16.77           | √               |
| k3         | 15.49                | √              | 17.08           | √               | 17.40           | √               |
| k4         | 826.38               | ×              | 912.5           | ×               | 1423.61         | ×               |
| k5         | 13055.6              | ×              | 13750           | ×               | 17708.3         | ×               |

Table 3. Positive sequence pilot impedance amplitude of L1 line during three-phase short circuit in RTDS simulation. (I_{set}=1A; Z_{set}=2*|DZ|=34.64Ω)

| Fault type | Transition resistance | Fault location | | Action | | Action | | Action |
|------------|----------------------|----------------|-----------------|-----------------|-----------------|-----------------|
|            | Z_{op}               | Z_{op}          | Z_{op}          |                 |                 |                 |
|            |                      |                |                 |                 |                 |                 |

| k1         | 15.50                | √              | 15.82           | √               | 16.45           | √               |
| k2         | 14.55                | √              | 14.82           | √               | 15.10           | √               |
| k3         | 16.46                | √              | 16.77           | √               | 16.78           | √               |
| k4         | 601.04               | ×              | 684.75          | ×               | 851.44          | ×               |
| k5         | 12152.8              | ×              | 34027.8         | ×               | 33680.6         | ×               |

4.2. Result analysis
In case of fault at any position in the area, the amplitude of each positive sequence pilot impedance is near the positive sequence impedance of the line, or even slightly greater than the positive sequence impedance of the line, but they all fall within the action selection range of the protection criterion type, which can meet the reliability and selectivity of the protection.

In case of out of area fault, the amplitude of each pilot impedance is much greater than the positive sequence impedance of the line, and falls outside the action selection range of the protection criterion type, so the protection is reliable and does not act.

In case of short-circuit fault with different transition resistors, the amplitude of positive sequence pilot impedance does not affect the judgment of the result, whether in zone fault or out of zone fault.

5. Conclusion
Based on the interconnection between flexible DC transmission system and AC power grid, proposes a pilot protection scheme based on positive sequence pilot impedance amplitude, and carries out relevant theoretical analysis and simulation verification. The simulation results show that the amplitude of positive sequence pilot impedance is much larger than that of line positive sequence impedance in case of out of zone fault; In case of fault in the area, the amplitude of positive sequence pilot impedance is approximately equal to the positive sequence impedance of the line, and there is little difference between them. The protection has the advantages of easy setting, strong resistance to transition resistance, no dead zone in the whole line, phase separation protection and optional function, and can be applied to more complex operation environment. The calculation results of positive sequence pilot impedance show that the pilot protection proposed in this paper can reliably and quickly identify various fault states.

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