Study on the Performance of Current Differential Protection in UHVDC Hierarchical Connection Mode

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Abstract. UHVDC hierarchical connection mode resulting in a very close electrical coupling between the AC and DC hybrid systems, with a very complex fault characteristic. In order to analyze the adaptability of line differential protection in the UHVDC hierarchical access AC grid, a certain ±800 kV UHVDC hierarchical access project is taken as the research object. The equivalent model of AC system, the characteristics of equivalent power frequency variation and harmonics in equivalent model are analyzed. Then the adaptability of steady-state current differential protection is analyzed. Finally, the analysis results is verified based on PSCAD/EMTDC simulation.

Introduction

In order to implement the National Action Plan on Prevention and Control of Air Pollution, domestic grid companies have completed and operated a number of UHVDC transmission projects. With the constant construction and development of DC transmission projects, a multi-infeed DC access system has been formed in South China and East China. In order to avoid a series of problems brought about by receiving end acceptance, voltage support and other aspects brought by DC single-layer access, domestic scholars first proposed a way of UHVDC hierarchical access to the AC power grid [1], DC inverter station of high and low converter are respectively connected to the 500 kV/1000 kV receiving-end via converter transformer, such as ±800 kV Ximeng-Taizhou UHVDC transmission project, which solves this problem from the grid structure.

More studies have been carried out in the overall design of DC control system [2-3] and the coordinated control of power [4] in the hierarchical access system. The study of the AC protection action under the condition of DC feeding mainly focuses on the influence of the DC system harmonics on the traditional AC protection [5]. At present, much more attention is payed to the influence of the dynamic characteristics of DC system on AC protection during the fault transient process [6]. In [7], the influence of DC system commutation failure on AC protection is analyzed by electromagnetic transient simulation. The influence of the commutation failure of DC system on the direction protection of power frequency variation by establishing the impedance variation model of power frequency variation is comprehensively analyzed [8]. Differential protection is the main line protection. In the new DC hierarchical connection mode, how is the adaptability of differential protection? The research in this area is still relatively small.

In this paper, a certain ±800 kV UHVDC access project is taken as the research object. The equivalent model of AC system, the characteristics of equivalent power frequency variation and harmonics in equivalent model are analyzed. Then the adaptability of steady-state current differential protection is analyzed. Finally, the correctness of the analysis results is verified based on PSCAD/EMTDC simulation.
Model Analysis of a Hybrid System with UHVDC Hierarchical Connection

Under the UHVDC hierarchical connection mode, the overall structure of the DC control system is basically the same as that of the ordinary UHVDC. However, since the receiving-end of DC system needs to coordinate with the two AC systems, there is a big difference of the structure and commonality of the control system of the inverter between the UHVDC hierarchical connection mode and the ordinary UHV. UHVDC hierarchical access system structure shown in Fig. 1.

![Figure 1. Schematic of the hierarchical connection to AC system for a ±800 kV UHVDC project.](image)

The rectification side of the UHVDC hierarchical access system is connected with the three-winding transformers in the form of two series of 12-pulse converter in series to the same voltage level bus. Where $T_{r1}$ and $T_{r2}$ are the conversion ratio of the converter transformer, $Z_r$ is the equivalent impedance of the rectifier side AC system; $U_r$ is the commutation bus voltage of the rectifier side; $E_r$ is the constant voltage source of the rectifier side AC system.

The inverter side of the system also adopts two groups of 12-pulse converter in series to be respectively connected with the three-winding transformer and connected to different voltage level buses; $I_d$ is the direct current; $U_{d1}$ and $U_{d2}$ are the inverter side DC voltage of loops 1 and 2, respectively; $U_d$ is the sum of $U_{d1}$ and $U_{d2}$ of the entire inverter side; $U_1$ and $U_2$ are the RMS voltages of the AC side of inverter side with different voltage levels; $T_1$ and $T_2$ are the transformers ratio; $Z_1$ and $Z_2$ are the equivalent impedance of the AC system; $Z_{12}$ is the equivalent contact impedance between the converter bus 1 and 2; $I_{ac1}$ and $I_{ac2}$ are respectively 1 000 kV and 500 kV DC commutation bus are injected into the AC power system of the receiving end; $E_1 \angle \theta_1$, $E_2 \angle \theta_2$ are the constant voltage source of the receiving end system; $B_{c1}$ and $B_{c2}$ are the reactive power compensation devices of the receiving end system; $P_{ac1}$ and $P_{ac2}$ are respectively the active power delivered to the system loop 1, 2 of the AC receiving end; $P_{d}$ is the active power on the DC transmission line power.

Fault Characteristics Analysis

For the AC-DC hybrid system, the superposition principle shows that both the normal operation and the fault status of the AC/DC system are decided by the DC system and the AC system together. The system structure when the AC system power is used alone as shown in Fig. 2 a), and Fig. 2 b) shows the system structure when the DC system power is used alone. Since the zero sequence current on the AC side can flow through the commutation transformer, the impedance of the commutation transformer also becomes part of the AC system network.
If a ground fault occurs at the point K of the AC system and a commutation failure of the DC system is caused, the amount of electric power at the protection installation can be expressed as:

\[ E_{\phi} = F_{ac}(U_{\phi,eq}) + F_{dc}(I_{\phi}) \]  

(1)

Where: \( U_{\phi,eq} \) is the AC grid voltage source; \( I_{\phi} \) is the equivalent current source injected into the AC grid by the DC system after the commutation failure; and \( E_{\phi} \) is the electric quantity of the phase.

After the AC fault occurs, the AC system \( F_{ac}(U_{\phi,eq}) \) can be obtained according to the network topology and the pre-fault operating state, while \( F_{dc}(I_{\phi}) \) is dynamically changing. Due to the nonlinearity of the inverter, \( F_{dc}(I_{\phi}) \) wave and each harmonic component, they also change over time in the transient process, that is to say, the dynamic phasor with time-frequency domain characteristics. Therefore, the key to obtaining \( E_{\phi} \) is to obtain the change of the \( F_{dc}(I_{\phi}) \) power frequency component in the transient process after the fault. Since the existing principle of line differential protection is mainly based on the variation of power frequency / power frequency, only the change of \( I_{\phi} \) power frequency component in the transient process is considered in this analysis, which helps to reveal the effect of commutation failure on the AC power grid Dynamic protection mechanism of influence.

\( I_{dc1} \) leads the phase voltage \( U_{bus} \) when the DC system is operating normally. \( I_{dc1} \) is located in the first quadrant if the phase voltage \( U_{bus} \) is taken as the reference. It should be pointed out that since the DC receiving end is generally close to the load center of the regional power grid, the full compensation of reactive power compensation is usually adopted on the inverter side. \( I_{dc,eq1} \) and \( U_{bus} \) in normal operation can be regarded as in-phase. The normal operation of the voltage and current vector relationship shown in Fig. 3.

Figure 2. Superimposed schematic diagram.

Figure 3. Normal operation of the voltage and current vector diagram.
Since the inverter side reactive power consumption is about 50% ~ 60% of the DC power, the phase difference $\phi$ between the equivalent power frequency current $I_{dc1}$ and the AC phase voltage $U_{bus}$ is approximately equal to 30°, that is, the amplitude of $I_{cap1}$ is about half of $I_{dc1}$. After the fault full current amplitude decreases, and the more serious the fault, the current amplitude decreases. After the fault full current phase angle ahead, and the more serious the degree of fault, the angle of the full current phase angle is bigger. After the fault full current phase changes shown in Fig. 4.

After the fault, the magnitude of the current fault component increases, and the more serious the fault is, the more the magnitude of the current fault component increases. The phase of the current fault component rotates counterclockwise about the opposite phase of the normal voltage, mainly behind the opposite phase of the normal voltage. Only in the case of a particularly serious fault, the phase of the current fault component slightly leads the opposite phase of the normal voltage. After the fault current fault component phase changes is shown in Fig. 5.

According to the superposition principle, the current after the fault can be decomposed into the sum of the load current and the fault component current before the fault. The following analysis of the DC layered access fault component current differential protection adaptability.

For the case of not considering the DC system, when ignoring the line capacitance current, it can be known that when the line MN breaks down, the amount of operation and the amount of braking respectively,

$$I_{d(ac)} = |I_{M1} + I_{N1}| = |(\Delta I_{acM1} + I_L) + (\Delta I_{acN1} - I_L)| = |\Delta I_{acf}|$$

The expression of $\Delta I_{acf}$ is shown in Eq.2.

$$I_{r(ac)} = |I_{M1} - I_{N1}| = |(\Delta I_{acM1} + I_L) - (\Delta I_{acN1} - I_L)| = k|\Delta I_{acf} + 2I_L|$$

Comparing with Eq.2 and Eq.3, the current load component is added to the braking load in different parts of the steady-state criterion and the fault component criterion, which adds an influencing factor. Easily lead to the differential protection of the move. When the load current is small, there is $\Delta I_{acf} >> 2I_L$. At this moment, the influence of load current can be neglected, that is, the influence of DC system on the fault component is similar. When the line load current is large, the load current $I_L$ is larger and the load current $I_L$ occupies the dominant position in the brake current $I_r$, so the disadvantage of the DC system to the brake amount can be neglected. How to consider the influence of heavy load on the...
criterion of steady state in power network. In general, the influence of DC system on steady-state criterion of current differential protection is smaller than that of fault components.

**Simulation Verification**

A ± 800 kV UHHVDC hierarchical access to 500/1000 kV AC system unipolar equivalent hybrid system model is built in the PSCAD simulation platform, the DC system uses dual 12-pulse 400 kV + 400 kV converter rated DC power of 5000 MW, rated DC current of 6.25 kA. The converter's arc-extinguishing angle is 22°, and the steady-state operating voltages of the two ends of the system are respectively 520 kV and 1050 kV. Thévenin equivalent model of equivalent impedance of the terminal AC system is adopted, the frequency of AC system is 50Hz, and the corresponding parameter is \( Z_1 = 10.67 + j42.7 \Omega, Z_2 = 5.335 + j21.35 \Omega, Z_{12} = 50 + j973.9 \Omega \). A-phase ground fault occurs on line L1, DC system commutation fails. Fault occurred at 0s, fault duration 50ms, sampling frequency of 4000Hz. The full-cycle Fourier algorithm is used to calculate the fundamental component of current, the accurate calculation results can be obtained after 20ms.

The simulation results of the operating current (\( \Delta I_d \)) and the braking current (\( \Delta I_r \)) with larger transition resistance (\( R = 80\Omega \)) are shown in Fig. 6. A metallic ground fault is shown in Fig. 7.

![Figure 6. Larger transition resistance when the operating current and braking current changes.](image)

![Figure 7. Metal grounding action current and braking current changes.](image)

From the simulation results, it can be seen that the operating current and the braking current becomes smaller with larger transition resistance. Comparing Fig.6 to Fig.7, when the transition resistance is large, the current differential protection may be refused to operate; when the transition resistance is small, the DC effect is smaller, the protection action is correct.

**Summary**

When analyzing the influence of DC system feed-in on AC system protection, it is assumed that the DC system is equivalent to a voltage-controlled current source. The voltage on the inverter side is
determined by the AC system. The DC system uses the current injected into the AC system to affect the protection of the exchange system. Since the equivalent current injected into the AC system by the DC system becomes different under different fault levels, the influence on the AC system protection is also different.

For differential protection of transmission lines, the hierarchical access of the DC system affects the fault component of the AC system by injecting the equivalent current component whose phase is different from the AC system current. When the transition resistance is large, the current differential protection may be refused to operate.

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References


