Analysis of Fault Characteristics for UHVDC Hierarchical Connection to AC Grid

Hong Cao¹, Xingguo Wang¹, Min Xie²
1 State Key Laboratory for Security and Energy Saving, China Electric Power Research Institute, Beijing, 100192, China.
2 State Grid Anhui Electric Power Company, Hefei, 230021, China.
hongcao16@163.com

Abstract. UHVDC transmission project will adopt hierarchical connection mode at its receiving end with its high and low converters integrated to 500 kV and 1000 kV AC grids respectively on inverter side. The short-circuit fault at AC line of hierarchical connected UHVDC transmission system is a serious threat to the safe and stable operation of the system. In this paper, the equivalent model of UHVDC hierarchical connection to AC Grid is proposed. The dynamic phasor theory is used to analyse the fault characteristics of UHVDC system equivalent fundamental frequency current. When the AC fault occurs at the distal of the converter station, the UHVDC system equivalent power frequency current shows a decreasing trend; When the AC fault occurs at the proximal of the converter station, a high current occurs in the UHVDC system equivalent fundamental frequency current. RTDS model simulation verified that the theoretical analysis result is correct and established foundation to the subsequent protection impact study.

1. Introduction

Compared with the multi-infeed UHVDC transmission mode, UHVDC hierarchical connection to AC Grid means that the inverter side is connected to 1000kV and 500kV voltage level power grids respectively, which has the characteristics of low engineering cost and safe and stable operation of the power grid. It can effectively improve the voltage support capability of the receiving network. By directing the UHVDC power of the transmission to be properly distributed in different receiving circuits, the advantages of the transmission capacity of the two-stage power grid can be fully utilized[1-2].

At present, the research on UHVDC hierarchical connection to AC Grid mostly focuses on access mode [3-4], stability [5-6], control strategy [7], etc. Few literatures mention the fault characteristics of UHVDC hierarchical connection to AC Grid and their impact on protection. The short-circuit fault at AC line of hierarchical connected UHVDC transmission system is a serious threat to the safe and stable operation of the system. Therefore, it is urgent to study the fault characteristics of the UHVDC hierarchical connection to AC Grid. In this paper, the equivalent model of UHVDC hierarchical connection to AC Grid is proposed. The dynamic phasor theory is used to analyze the fault characteristics of UHVDC system equivalent fundamental frequency current. When the AC fault occurs at the distal of the converter station, the UHVDC system equivalent power frequency current shows a decreasing trend; When the AC fault occurs at the proximal of the converter station, a high current occurs in the UHVDC system equivalent fundamental frequency current. RTDS model simulation verified that the theoretical analysis result is correct and established foundation to the subsequent protection impact study.
simulation verified that the theoretical analysis result is correct and lays the foundation for the subsequent protection impact study.

2. Equivalent Circuit

In severe cases, the AC side fault will cause large fluctuations in the AC bus, resulting in a commutation failure. At this time, the fluctuation of the direct current will increase, and the conduction of each valve will also change, so the current injected into the alternating current system will also change accordingly. Therefore, relative to pure AC system in power network of receiving end, the access of the UHVDC system is equivalent to the addition of a voltage-controlled current source \( i_{dc} = f(U_{bus}) \), as shown in Figure 1. When the AC/DC hybrid system is in normal operation, \( i_{dc} \) behaves as a stable constant current source; In the event of a UHVDC system failure or disturbance that causes the commutation failure in the UHVDC system, Since the UHVDC system contains a large number of non-linear power electronics and rapid regulation of the control system in the UHVDC system, \( i_{dc} \) appears as a current source with complex harmonic components.

The equivalent power frequency current injected into the AC grid by the UHVDC system is:

\[
i_{pl,eq} = I_{pl} + I_{cap}
\]  

(1)

Where: \( I_{pl} \) is the current power frequency component of the UHVDC system injected into the AC grid through the inverter during the transient process; \( I_{cap} \) is the power frequency component of the reactive power compensation branch current \( i_{cap} \) injected into the AC grid by the UHVDC system.

![Figure 1. UHVDC system equivalent diagram](image1)

![Figure 2. Schematic diagram of AC/DC hybrid system with UHVDC hierarchical connection to AC Grid](image2)

Schematic diagram of AC/DC hybrid system with UHVDC hierarchical connection to AC Grid is shown in Figure 2. \( Z_{c1} \) and \( Z_{c2} \) are the reactive power compensation branch impedance, \( Z_{12} \) is the connection impedance of the two-voltage AC grid, and \( I_{dc1} \) and \( I_{dc2} \) are the equivalent current of the high-end valve group and the equivalent current of the low-end valve group in UHVDC hierarchical connection system, \( R_s \) is the transition resistance, \( Z_{s1} \) and \( Z_{s2} \) are the equivalent impedance of the AC system, \( E_1 \) and \( E_2 \) are the equivalent internal potentials. When the AC grid
failure, due to the nonlinear characteristics of the converter, the UHVDC system equivalent currents is dynamically changing, which can be considered as dynamic phasor with time-frequency domain characteristics.

3. Fault Characteristics of UHVDC System Equivalent Fundamental Frequency Current

In this paper, the model of the UHVDC system is established by dynamic phasor theory, and the change of UHVDC system equivalent fundamental frequency current after AC fault is analytically calculated.

Based on the time-varying Fourier transform, the waveform of a signal \( x(\tau) \) in the time domain can be expanded into a time-varying Fourier series in any interval \( \tau \in (t-T, t) \):

\[
x(\tau) = \sum_{k=-\infty}^{\infty} X_k(t)e^{jk\omega_0\tau}
\]

(2)

Where: \( \omega=2\pi/T \), \( X_k(t) \) is the k-th time-varying Fourier coefficient, and the kth coefficient can be obtained by:

\[
X_k(t) = \frac{1}{T} \int_{t-T}^{t} x(\tau)e^{-jk\omega_0\tau} d\tau = \langle x \rangle_k (t)
\]

(3)

Where \( X_k(t) \) is a function of time. When the window under study (width T) moves along the time axis on the waveform \( x(\tau) \), the phasor \( X_k(t) \) changes.

Under normal operating conditions, the converter valves are sequentially turned on in sequence, and the relationship between the voltage and current on both sides of the AC and UHVDC can be expressed as:

\[
\begin{align*}
  u_{aS} & = u_{a}S_a + u_{b}S_b + u_{c}S_c \\
  i_{aS} & = i_{a}S_a \\
  i_{bS} & = i_{b}S_b \\
  i_{cS} & = i_{c}S_c
\end{align*}
\]

(4)

Where: subscript "i" means inverter, \( u_{a} \) is inverter side UHVDC voltage, \( i_{a} \) is inverter side UHVDC current; \( S_a \), \( S_b \) and \( S_c \) are abc three-phase voltage switching functions respectively; \( S_a \), \( S_b \) and \( S_c \) are respectively Three-phase current switching function. The switching function is to treat the converter valve as an electronic switch. The square wave has an amplitude of 1 during the conduction of the converter valve and a value of 0 during the off period.

It can be seen from equations (4) and (5) that the dynamic phasor form of the alternating current on the inverter side is:

\[
I_{\varphi(k)} = \sum_{m} I_{dc(k-m)}S_{\varphi(m)}
\]

(5)

Where: \( k \) and \( m \) represent the order of the corresponding dynamic phasors, respectively, and \( \varphi \) is the three phases a, b, and c. Equation (6) is a dynamic phasor model for the current injected into the AC grid by the converter. Since the existing protection principle is mainly based on the power frequency component, this paper analyzes the variation of the equivalent current power frequency component injected into the AC system through the inverter during the transient process, that is, taking \( k=1 \) in equation (6). 1, get:

\[
I_{\varphi1} = \sum_{m} I_{dc(1-m)}S_{\varphi(m)}
\]

(6)

Substituting equation (7) into equation (1):

\[
I_{dc,eq} = \sum_{m} I_{dc(1-m)}S_{\varphi(m)} + I_{cap}
\]

(7)

It can be known from equation (8) that the equivalent fundamental frequency current of the UHVDC system is related to the three-phase current switching function after the failure of the AC system. The switching function is directly affected by the commutation bus voltage. When the AC fault occurs at the distal of the converter station, the voltage of the commutation bus is less affected.
Due to the influence of the control system, the equivalent fundamental frequency current of the UHVDC system decreases. When the AC fault occurs at the proximal of the converter station, the bus voltage is greatly affected, and the UHVDC system equivalent fundamental frequency current has a high current.

4. Simulation
Based on parameters of the domestic ±1100 kV UHVDC project with hierarchical connection mode, as shown in Fig.3, a simulation model is built on RTDS. The UHVDC inverter side is layered into a 500 kV/1000 kV AC hierarchical power grid. The UHVDC rated voltage is ±1100kV and the UHVDC rated current is 5.45KA.

![Figure 3. Structure of UHVDC system with hierarchical connection mode](image)

When the A-phase fault is happened at the proximal of the 1000kV AC grid, the fundamental frequency current amplitudes at the 500kV commutating bus and the 1000kV commutating bus are shown in Figure 4 and Figure 5 respectively.

![Figure 4. Fundamental frequency current amplitude waveform at 1000kV commutation bus](image)

When the A-phase fault is happened at the distal of the 1000kV AC grid, the fundamental frequency current amplitudes at the 500kV commutating bus and the 1000kV commutating bus are shown in Figure 6 and Figure 7 respectively.

![Figure 5. Fundamental frequency current amplitude waveform at 500kV commutation bus](image)

It can be seen from Figure 4-7, when the distance between fault location and the commutating bus is larger, the UHVDC system equivalent fundamental frequency current is smaller, and it shows a downward trend in the initial stage of the fault. Simulation results of 1000kV distal and proximal faults are similar to those of 500kV distal and proximal faults, which are not given in this paper due to the limitation of length.
5. Conclusion
In this paper, the equivalent model of UHVDC hierarchical connection to AC Grid is proposed. The dynamic phasor theory is used to analyse the fault characteristics of UHVDC system equivalent fundamental frequency current. When the AC fault occurs at the distal of the converter station, the UHVDC system equivalent power frequency current shows a decreasing trend; When the AC fault occurs at the proximal of the converter station, a high current occurs in the UHVDC system equivalent fundamental frequency current. RTDS Simulation tests verify the validity of the theoretical analysis. It is known from the equivalent fundamental frequency current characteristics of the UHVDC system that the distance protection performance of AC system is seriously affected, and the adaptability of the distance protection needs further study.

6. References
[1] Zhenya Liu, Xiaohui Qin, liang Zhao, et al. Study on the Application of UHVDC Hierarchical Connection Mode to Multi-infeed HVDC System. J. Proceedings of the CSEE, 2013, 33(10):1-7.
[2] Yi Tang, Bin Chen, Qi Wang, et al. Analysis on Reactive Power and Voltage Coupling Characteristics of Hybrid System for UHVDC Hierarchical Connection to AC Grid. J. Power System Technology, 2016, 40(4):1005-1011.
[3] Yu Shen, Yongxin Xiong, Wei Yao, et al. Comprehensive Evaluation for Receiving End Connection Scheme of ±1100kV UHVDC Power transmission. J. Electric Power Automation Equipment, 2016, 40(4):1005-1011.
[4] Sun W, Rong F, Zhou Z, et al. Analysis on the operating characteristic of UHVDC hierarchical connection mode to AC system. J. Proceedings of the CSEE, 2013, 33(10):1-7.
[5] Wang C, Zhu L, Chen B, et al. Analysis on voltage stability of hybrid system with UHVDC hierarchical connection to AC grid. Power Electronics & Motion Control Conference, 2016.
[6] Jia N, Qi W, Yi T, et al. Study on the characteristics of AC/DC hybrid system under UHVDC hierarchical connection mode. Power Electronics & Motion Control Conference, 2016.
[7] Yongxin Xiong, Yu Shen, Wei Yao, et al. Improved Additional Power Coordinated Control of ±1100kV UHVDC System With Hierarchical Connection Mode. J. Power System Technology, 2017(11):3448-3456.

Acknowledgments
This work is supported by Science and Technology Project of State Grid Corporation of China: Research on relay protection optimization strategy of ±1100kV DC/ 1000kV AC hybrid power system (SGAH0000TKJS1800050).