Study on System Operation Characteristics of UHVDC Under Hierarchical Connection Mode

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Abstract. In order to effectively solve the problem of voltage support in receiving end of the multi-infeed DC system, the UHVDC connected to AC network under hierarchical connection mode is proposed. In this paper, the simulation model of UHVDC considering interlayer coupling is set up by PSCAD/EMTDC electromagnetic transient simulation software. The difference of AC system strength between hierarchical connection mode and traditional connection mode is compared. The variation characteristics of the effective interlayer short circuit ratio of the hierarchical connection AC system under different coupling strengths are simulated. By studying the influence law of the interlayer impedance on the steady-state system operation characteristics and the system commutation failure characteristics after the fault, the interaction between the different AC systems of the inverter side is analysed. The results of this paper can provide theoretical support for the operation stability of UHVDC hierarchical connection mode transmission system.

1. Introduction
As HVDC power transmission system has the advantages of large transmission capacity, low loss, flexible power regulation inversion, high transmission reliability and strong asynchronous connection ability, it is widely used in long-distance, large-area power grid interconnection and large-capacity transmission[1]. At present, HVDC transmission projects are almost based on grid commutation converter technology. Thyristors are used as converters, which do not have self-switching ability. Therefore, the receiving AC system must provide sufficient commutation voltage and reactive power to ensure the normal switching of thyristors, otherwise the DC system will have commutation failure[2]. Commutation failure will cause serious consequences such as dramatic increase of DC current, shortened life of converter valves, reduction of DC transmission power and voltage instability of weak AC system on the inverter side. Continuous commutation failure will easily lead to power reduction operation of DC system, even lead to valve blocking or pole blocking, which will affect the normal operation of DC transmission system and threaten the safety and stability of the whole power system[3]. In order to effectively solve the problem of voltage support in the receiving end of the multi-infeed DC system, the hierarchical connection mode of UHVDC is proposed[4,5]. Under hierarchical connection mode, the rectifier side maintains the original connection mode, while the high-end and low-end converters on the inverter side are connected to two AC grids of different voltage levels[6]. From the economic point of view, the hierarchical connection mode can significantly reduce the investment in power grid[7]. However, the topology of UHVDC transmission system under hierarchical connection mode is more complex, and the interaction between AC/DC systems and the two AC systems of
receiving end is more prominent. Because the thyristor is also used as the core component of the converter, and the receiving AC system of the hierarchical connection system includes more than one AC circuit\cite{8}, each AC circuit and the connection between different AC circuits will both affect the operation characteristics of the hierarchical connection system. Therefore, it is necessary to study the characteristics of DC system under hierarchical connection mode.

This paper studies the influence of the different coupling strengths (interlayer connection impedance) between two AC systems of inverter side under hierarchical connection mode on the steady-state operation characteristics of the system and the commutation failure characteristics of the system under faults by simulation analysis\cite{9-10}. The interaction between different AC systems of inverter side under steady-state and transient conditions is analysed. The work of this paper can provides theoretical support for transmission stability of UHVDC transmission system under hierarchical connection mode.

2. UHVDC Hierarchical connection Model Considering Interlayer Coupling

The electrical wiring diagram of ±1100kV Changji-Guquan UHVDC transmission project under hierarchical connection mode is shown in figure 1.

![Figure 1. Electrical wiring diagram of ±1100kV Changji-Guquan UHVDC system under hierarchical connection mode](image)

Each pole of the converter station is composed of double twelve-pulse converters in series. Changji station is connected with 750kV AC bus as rectifier station, and Guquan station is used as inverter station. Its double high-end converter is connected to 500kV AC bus by high-end converter transformer, and the double low-end converter is connected to 1000kV AC bus by low-end converter transformer. The hierarchical connection mode is equivalent to dividing the whole DC system into two half-capacity DC systems. AC filters, reactive power compensators and shunt capacitors are independently configured and connected to the two classes of converter buses according to the 500kV and 1000kV levels. Converter buses of different levels are connected by connecting transformers and tie lines. In the bipolar operation mode, the positive and negative electrodes are operated in monopolar mode, and the DC current in the two poles maintains a balanced state in normal operation.

Observing the receiving end AC system from the converter bus, the structure of the receiving end AC system can be equivalent to that shown in figure 2. In the figure, $Z_i$ and $Z_l$ are equivalent impedance of 1000kV and 500kV converter buses, $Z_k$ is connecting-line impedance between two converter buses, the ratio of connecting-transformer $k > 1$.

![Figure 2. Diagram of hierarchical connection mode of receiving end AC System](image)
Perform Pi-type equivalence to connecting-transformer. By means of multi-terminal Thevenin equivalence theory, the admittance matrix of equivalent network node of receiving system is obtained as follows\(^{[11]}\):

\[
Y = \begin{bmatrix}
\frac{1}{Z_{ij}} + \frac{1}{Z_{ij}} & -\frac{k}{Z_{ij}} \\
-\frac{k}{Z_{ij}} & \frac{1}{Z_{ij}} + \frac{k^2}{Z_{ij}}
\end{bmatrix}
\]

(1)

Among them, \(Z_{ij}\) represents the interlayer connection impedance, whose value is \(k^2Z_T + Z_L\), and \(Z_T\) is equivalent to the impedance of transformer on the secondary side.

It can be seen that the different value of connection impedance \(Z_{ij}\) will lead to the different tightness of interlayer connection between 500kV and 1000kV AC systems at the receiving end, and the different effect of interlayer interaction.

3. The steady-state operation characteristics of the system under hierarchical connection mode

3.1 Research on AC System Strength under Hierarchical Access

In hierarchical connection mode, the hierarchical effective short circuit radio (HESCR) is usually used to express the AC system strength\(^{[12]}\). It is obvious that the HESCR is related to the connection impedance \(Z_{ij}\). In order to analyse the impact of hierarchical connection mode on AC system strength, the changes of HESCR in three cases are compared. The results are shown in table 1.

Mode 1: Non-hierarchical, high-end and low-end converters both are connected to 500kV AC bus.

Mode 2: Non-hierarchical, high-end and low-end converters both are connected to 1000kV AC bus.

Mode 3: Hierarchical connection mode, high-end and low-end converters are connected to 500kV and 1000kV AC buses respectively, and the connection impedance \(Z_{ij}=5+100j\).

| Connection mode | AC bus   | HESCR   |
|-----------------|---------|---------|
| Mode 1          | 500kV   | 4.69    |
| Mode 2          | 1000kV  | 5.81    |
| Mode 3          | 500kV/1000kV | 8.10/11.11 |

As can be seen from the table above, under mode 1, the AC system is a medium-strong AC system. Under Mode 2 and 3, the AC system is a strong AC system. Compared with the traditional connection mode, the HESCR of each AC system under hierarchical connection mode has nearly doubled, that is to say, the hierarchical connection mode improves the voltage support capability of AC systems.

The HESCR of 500kV and 1000kV AC system at receiving end is calculated respectively under different interlayer connection impedance. Considering that the overall resistance \(R\) of AC system is always less than reactance \(X\), and referring to the impedance angle of connection impedance of existing ±800kV Ximeng-Taizhou hierarchical connected HVDC transmission project is 80 degrees, the impedance angle of calculation in this paper is set in the range of 75 degrees to 85 degrees, the results are shown in figure 3.

![Diagram of the variation of HESCR with connection impedance](image-url)
It can be found from the graph that the $HESCR$ of AC system with hierarchical connection mode is only related to the impedance model of interlayer connection, and is basically independent of the impedance angle. The $HESCR$ of 1000kV AC system decreases with the increase of interlayer connection impedance, while that of 500kV AC system increases with the increase of interlayer connection impedance, and the change rate of interlayer connection impedance decreases gradually. However, the $HESCR$ of 1000kV AC system is always greater than 500kV AC system, that is to say, the voltage support capability of 1000kV AC system is always stronger than that of 500kV AC system.

3.2 Effect of Interlayer Connection Impedance on System Operation under Steady State

On the basis of PSCAD simulation model of ±1100kV UHVDC under hierarchical connection mode considering the interlayer connection impedance of different impedance models and impedance angles of interlayer connection impedance are set up respectively. The simulation results show that the active power transmitted to AC system and the active power transmitted from 500kV to 1000kV AC bus in steady-state operation varies with the impedance models and impedance angles of interlayer connection impedance. The impedance angle is set as 75 degree, 80 degree and 85 degree respectively. The simulation results are shown in figure 4 and figure 5.

From figure 4, it can be found that with the increase of connection impedance, the active power $P_{ac500}$ transferred to 500kV AC system increases gradually, while the active power $P_{ac1000}$ transferred to 1000kV AC system decreases gradually. With the increase of connection impedance, the change rate of power decreases gradually, and the power transferred to 500kV and 1000kV AC system tends to be the same.

From figure 5, it can be seen that the active power $P_{500-1000}$ transferred among layers is much larger than the reactive power $Q_{500-1000}$. That is to say, active power is dominant in power transfer among layers in steady state. $P_{500-1000}$ and $Q_{500-1000}$ decrease with the increase of connection impedance.

For the hierarchical connection model, the active power transferred from the rectifier side to the two AC buses is equal to the sum of the active power transferred to the AC system and the active power.
transferred among the two AC buses. The active power transferred from the rectifier side to the two AC buses is drawn as shown in figure 6. It can be seen that the active power transferred from the rectifier side is always about 5600 MW, independent of the connecting impedance value.

According to the figures above, the operation of the hierarchical connection system in steady state is mainly related to the connection impedance models. The magnitude of the interlayer connection impedance will affect the active power transferred from the inverter side to two AC systems in steady state. The smaller the connection impedance, the stronger the interaction between the two-layer AC system, the greater the power transmission between AC buses, and the more unbalanced the active power transferred to the two AC systems. On the contrary, the larger the connection impedance, the weaker the interaction, the smaller the power transmission between layers, and more consistent the active power received by AC systems.

4. Transient commutation failure characteristics in hierarchical connection mode

4.1 Interlayer Connection Impedance and MIIF

According to the definition of interaction strength between converter stations in multi-infeed HVDC transmission system given by CIGRE HVDC Working Group, when the voltage of converter bus $i$ decreases by 1% due to disturbance, the multi-infeed interaction factor ($MIIF_j$) of converter bus $j$ can be expressed as

\[
MIIF_j = \frac{\Delta U_j}{1\% U_i}
\] (2)

For the DC hierarchical connection mode, there is electrical coupling between the two layers of different voltage levels of the receiving system, which has certain interaction with each other. We can also introduce $MIIF$ as the voltage interaction factor between the two AC systems. Obviously, $0 < MIIF < 1$. The larger the $MIIF$, the stronger the interaction between two layered AC systems.

The relationship between voltage interaction factor $MIIF$ and interlayer connection impedance $Z_{ij}$ is studied. On the basis of the PSCAD simulation model of ±1100kV UHVDC under hierarchical connection mode, the three-phase grounding faults of 500kV and 1000kV AC system are set up respectively for 50ms. The relationship between $MIIF$ and connection impedance model [$Z_{ij}$], connection impedance angle $\theta$ is obtained, as shown in figure 7 and figure 8. $MIIF_{21}$ is the voltage interaction factor for 1000kV AC bus when the voltage of 500kV AC bus decreases; $MIIF_{12}$ is the voltage interaction factor for 500kV AC bus when the voltage of 1000kV AC bus decreases.
It can be seen that $MIIF_{21}$ decreases with the increase of connection impedance model and the change rate decreases with the increase of impedance angle when the impedance angle is constant; $MIIF$ increases slightly with the increase of impedance angle when the impedance value is constant. The influence of impedance angle can be neglected compared with that of impedance model on $MIIF$. Therefore, the impedance angle is selected as 80 degree in the follow-up simulation. Under the same fault, $MIIF_{12}$ is always larger than $MIIF_{21}$, indicating that 1000kV AC system has greater impact on 500kV AC system.

4.2 The influence of Interlayer Connection Impedance on the commutation failure characteristics

As the connection impedance between 500kV and 1000kV AC buses and the energy transfer between 500kV and 1000kV converter buses, when the voltage of one AC bus drops due to fault, the other AC bus will transmit reactive power to it through interlayer coupling to maintain the voltage stability of its bus. At this time, the AC system that would have failed in commutation may avoid commutation failure because of the energy transmission between layers.

Based on the PSCAD/EMTDC simulation model of ±1100kV Changji-Guquan UHVDC transmission project, a grounding fault of phase A is set on the 500kV AC bus of the inverter station, the grounding resistance is 6Ω, the time of fault occurrence is 0.5s, and the fault duration is 0.05s. The simulation is carried out respectively under the conditions of: (1) the inverter station is connected to 500kV AC system under traditional connection mode; (2) the inverter station is connected to 1000kV/500kV AC system under hierarchical connection mode and connection impedance is 20Ω. The extinction angle of the high-end and low-end converter, the valve current of Y-△ converter transformer, the effective value of phase A voltage of two AC buses, and waveform of single pole DC transmission power after the fault occurs is shown as figure 9 and figure 10. Since the thyristor needs a certain time to complete carrier recombination to restore the blocking ability, its deionization recovery time is about 400μs (about 7°for electrical angle). Considering the series elements error, the recovery time of the thyristor valve $\gamma_{\text{min}}$ is about 10°. Therefore, in the simulation, when $\gamma < 10^\circ$, the system will fail in commutation.
The power transfer between layers of 1000kV AC bus and 500kV AC bus of the hierarchical connection model is shown in figure 10.

It can be seen that in the non-hierarchical connection model, when the 500kV AC bus has a single-phase ground fault, commutation failure occurs during the commutation process of converter valve V6-V4 of Y-Δ converter transformer, the phase A voltage of the AC bus at the inverter side drops to 0.75p.u., the DC transmission power drops to 0, and the system returns to normal after the fault occurs for about 0.2s.
In the hierarchical connection model, when the 500kV AC bus has single-phase grounding fault, the voltage of 500kV AC bus at the inverter side drops to 0.85p.u., and the voltage of 1000kV AC bus drops to 0.95p.u.. The commutation valve has no commutation failure, and the DC transmission power only drops about 4% compared with the normal operation. The system returns to normal after the fault occurs about 0.1s.

In the hierarchical connection model, there exist power transmission between 1000kV AC bus and 500kV AC bus after the fault occurs. The maximum active power transmission reaches 8000 MW and the maximum reactive power transmission reaches 5000 MVar. Due to the effect of connection impedance, 1000kV AC bus has a certain voltage supporting effect on 500kV AC bus, which reduces the voltage drop of 500kV AC bus after the fault. In another word, the hierarchical connection mode avoids the failure of commutation, maintains the DC transmission power to a certain extent, and improves the stability of DC transmission system.

5. Conclusion
On the basis of ±1100kV Changji-Guquan UHVDC hierarchical connection transmission system, a PSCAD simulation model considering the interlayer connection impedance is built to study the system operation characteristics under the hierarchical connection mode, and the following conclusions are obtained:

(1) Compared with the traditional mode, the hierarchical connection mode improves the voltage support ability (HESCR) of AC system. When the interlayer connection impedance increases, the HESCR of 1000kV AC system decreases, and that of 500kV AC system increases, but the voltage support capacity of 1000kV AC system is always stronger than that of 500kV AC system.

(2) In the steady state, the operation of the hierarchical connection system is mainly related to the model of connection impedance. Active power is dominant in power transfer among layers. The lower the interlayer connection impedance, the stronger the interaction between the two AC systems, the greater the power transmission between AC buses, and the more unbalanced the active power transmitted to two AC systems. In the transient state, the MIIF decreases with the increase of connection impedance, and the fault of 1000kV AC system has a greater impact on 500kV AC system.

(3) When the single-phase ground fault occurs in AC system of the inverter side of the hierarchical connection system, there is power transmission between the two AC buses due to the interlayer connection impedance. The non-fault AC bus will have a certain voltage supporting effect on the fault AC bus, which reduces the voltage drop degree of the fault AC bus, and the commutation failure will be avoided. DC transmission power will be maintained to a certain extent, and the stability of DC transmission system will be improved.

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