Simulation Modeling and Analysis of UHVDC with Split Connection to 500 kV/1000 kV AC System

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ABSTRACT

The structure and function scheme of UHVDC with split connection are analyzed. The key aspects of the control system, such as voltage balance between high voltage converter and low voltage converter, transformer tap-changer (TCC) control and reactive power control, are analyzed and modeled. When an alternate current (AC) grid has a fault, the converter connects to the other normal AC grid in the inverter, which is controlled by the traditional commutation failure prediction (CFPRED) control strategy, will fail to commutate. In this paper, an improved CFPRED control strategy is proposed. The control strategy takes the CFPRED angle of the converter which connected to the fault AC network as the CFPRED angle of the converter which connected to the normal AC network. The electromagnetic transient simulation model of actual control system was established on the PSCAD/EMTDC, and the simulation results show that the improved CFPRED control strategy can ensure the converter commutate successfully which connected to the normal AC grid during the fault of another AC gird.

Keywords: UHVDC, PSCAD/EMTDC, split connection mode, improved CFPRED control.

INTRODUCTION

In recent years, with the deterioration of the ecological environment and the reverse distribution pattern of energy and load in China, we need to build long-distance, large capacity and multi-infeed energy transmission channels to transmit power to the load center [1-3], which provides a solution to above problems. The main problem of multi-infeed HVDC is whether the power grid can provide strong voltage support [4-6]. In the paper [7], it proposes that the UHVDC with split connection can improve the voltage support capability and guide the rational distribution of power flow in power grid.

The papers [8-14] study the control strategy of UHVDC under split connection mode, but the specific control strategy of the UHVDC is not pointed out. In addition, when an AC...
grid has a fault, the converter connected to the other normal AC grid in the inverter, which is controlled by the traditional CFPRFED control strategy, will fail to commutate.

In order to solve the above problems, the electromagnetic transient simulation model is established on PSCAD/EMTDC, which based on the Xilinhaote-Taizhou(XT)± 800kV UHVDC transmission project. An improved CFPRFED control strategy is proposed in this paper, and the simulation results show that the strategy can ensure the converter commutate successfully which connected to the normal AC grid during the fault of another AC grid.

**STRUCTURE AND FUNCTION SCHEME OF UHVDC WITH SPLIT CONNECTION**

![Figure 1. Split structure of control system for UHVDC with split connection.](image)

The split structure of the UHVDC control system under the split connection mode is shown in Figure 1. Bipolar control level: Under the split connection mode, 500/1000 kV system independent reactive power control function should be allocated in the bipolar control level, and reactive power control objective is AC bus voltage or reactive power exchange value. Polar control level: Under the split connection mode, the difference of transformer's tap changer between high voltage converter and low voltage converter, voltage and phase angle of AC system, which may lead to the difference of the operation voltage between the high voltage converter and low voltage converter. Converter control level: under the split connection mode, the closed loop control of current, voltage and firing angle \( \alpha \) in the pole control system need to be implemented in the converter control system, because of the series of high voltage converter and low voltage converter are connected to two different AC system.

**KEY POINTS OF SIMULATION MODELING**

Control of DC voltage balance

The calculation formula for the inverter side DC voltage

\[
 u_d = u_{d0} \cos \gamma - (d_x - d_r) \left( \frac{I_d}{I_{dN}} U_{d0N} + U_T \right)
\]

(1)

In the formula, \( U_{d0} \) represents actual no-load direct voltage 6 pulse group; \( U_{d0N} \) represents ideal no-load direct voltage 6 pulse group; \( I_d \) represents DC current; \( I_{dN} \) represents rated DC current; \( d_x \) represents inductance voltage drop; \( d_r \) represents resistance voltage drop; \( U_T \) represents voltage drop of converter; \( \gamma \) represents extinction angle.

Under single connection mode, the parameters of formula (1) are the same between high
voltage converter and low voltage converter. Therefore, the traditional UHVDC transmission project adopts the synchronous control of high and low transformer’s tap and the same reference value of $\gamma$ to achieve voltage balance of high voltage converter and low voltage converter. Under split connection mode, the traditional control mode leads to the voltage imbalance because of the different parameters of high transformer and low transformer. In this paper, the closed-loop control of the current, voltage and $\alpha$ in the inverter pole control system are put down to the converter control system. The high voltage converter and low voltage converter still work in the Alphamax inverter control (AMAX) mode and voltage balance between converter is realized by independent control of converter transformer’s tap-changer.

The block diagram of the converter firing angle control (CFC) under split connection mode is shown in Figure 2. In the picture, $U_{d\text{INV}}$ is the DC voltage on the inverter side, $I_{\text{ORD}}$ is current instruction generated by polar control, $I_d$ is the DC current on the inverter side, and $\text{Alpha}_\text{ORD}$ is the output firing angle instruction. Under normal condition, the output of the inverter side voltage control amplifier (VCA) is the upper limit of the current control amplifier (CCA), and the output of AMAX is the upper limit of VCA, where the $\gamma$ in the AMAX is 17°. Under split connection mode, $\text{Alpha}_\text{ORD}$ of the high voltage converter and low voltage converter are given by their respective CFC, which is different from traditional UHVDC.

The block diagram of TCC is shown in Figure 3. In the picture, $U_{d\text{M_INV}}$ is the earth to ground voltage at the middle point of the high voltage converter and the low voltage converter of the inverter, $U_{d\text{N_INV}}$ is the neutral line to the ground voltage, $R_L$ is the line

$$u_d = u_{d\text{INV}} - u_{dm\text{INV}} + I_d \cdot R_L$$  \hspace{1cm} (2)$$

Because of the independent control of the high voltage converter and low voltage converter, the $U_{d\text{INV}}$ in the above formula is not suitable for TCC control with split connection, so it needs modification.

$$u_d = (u_{d\text{INV}} - u_{dm\text{INV}} + \frac{I_d \cdot R_L}{2}) + (u_{dm\text{INV}} - u_{dN\text{INV}} + \frac{I_d \cdot R_L}{2})$$  \hspace{1cm} (3)$$

The block diagram of TCC is shown in Figure 3. In the picture, $U_{dM\text{INV}}$ is the earth to ground voltage at the middle point of the high voltage converter and the low voltage converter of the inverter, $U_{dN\text{INV}}$ is the neutral line to the ground voltage, $R_L$ is the line
resistance, and $U_{DEAD}$ is the voltage control limit value. Through the above controller configuration, on the one hand, the DC voltage can be controlled at 800 kV, on the other hand, the voltage balance of the two series converters can be guaranteed.

**Control of reactive power control**

Due to the short electrical distance between the two AC systems on the inverter side, the switching operation of a reactive power unit of an AC system may cause some disturbance to the voltage of another AC system. In paper [9], it demonstrates that the reactive power unit of the two AC systems can be controlled independently. Based on XT project designation specification, there active power of XT UHVDC with split connection at inverter side is controlled by the DC station control system, and the reactive power exchange or AC bus voltage is as the control target at rectifier side. The 500 kV/1000 kV AC bus reactive power exchange or voltage control is as control target respectively in the inverter side. The diagram of reactive power control is shown in Figure 4.

In the figure, $Q_{MAES}/U_{MEAS}$ is the measured value of reactive power/voltage; $Q_{DEAD}/U_{DEAD}$ is the limit value of reactive power/voltage; $Q_{REF}/U_{REF}$ is the reference value of reactive power/voltage set by operator; $Q_{INC}/U_{INC}$ is the instruction of input reactive compensation device; $Q_{DEC}/U_{DEC}$ is the instruction of remove reactive compensation device.

**NEW PROBLEM OF CFPRED IN UHVDC INVERTER SIDE UNDER SPLIT CONNECTION MODE**

**Limitation of predictive control function of traditional commutation failure**

The function of inverter side CFPRED is configured in the AMAX, as shown in Figure 5. Because of the high voltage converter and low voltage converter are connected to two AC systems respectively, the CFPRED function is independently configured. The increment angle of the high voltage converter is $AMIN_{CFPRED,500}$, and the increment angle of low voltage converter is $AMIN_{CFPRED,1000}$. The function of the CFPRED includes the AC fault detection module and the increment angle calculation module. The principle of AC fault detection is: ① By detecting the phasor of the three-phase voltage and when it is larger than the threshold value, it is considered that a single phase fault occurs. ② Based on an $α/β$ transformation of a three-phase voltage, when a three-phase AC voltage is malfunction, the vector of its $α/β$ will be reduced in comparison with the steady state value. When the output value of the AC fault detection module is larger than the threshold value, the increment angle
module converts the detection value to the corresponding increment angle of the CFPRED, which increases the commutation margin instantly and reduces the danger of commutation failure of the DC system.

\[ \beta = \arccos[\cos \gamma - 2 \cdot d_x \cdot \frac{I_b}{I_{dN}} \cdot \frac{U_{dIN}}{U_{d0}} - K(I_b - I_d)] \]  

(4)

In Figure 5, the formula (4) is used to modify the constant control. In transient state, the inverter has the characteristic of positive impedance, and the DC voltage increases with the increase of current. It is beneficial to improve the stability of the DC transmission system.

When an AC power grid has a fault and another AC grid is running normally, the converter connected to the failure AC grid will fail to commutate. The DC voltage decreases greatly on the inverter side, which leads to the rapid increase of DC current in the normal operating converter which connected to normal AC grid. By formula (4), the \( \beta \) in the normal operation converter is reduced, and the DC current is suppressed by increasing the voltage of the normal operation converter. In addition, the two AC systems with split connection mode are weak coupled. One AC power grid fault has little influence on the other AC system, and the increment angle produced by the CFPRED function in the converter which connected to normal AC power grid is very small. At the time of the failure of the AC system, the trigger delay angle of the normal operation converter basically maintains the angle before the failure.

The traditional CFPRED control strategy causes the continuous failure of the normal operation converter and leads to power oscillation of UHVDC system. Because of the increase of DC current, on the one hand, the overlap (\( \mu \)) of the commutation is increased; on the other hand, the \( \beta \) reduction in the normal operation valve group is reduced. The actual value of \( \gamma \) is far less than the \( \gamma \) reference value. The function of CFPRED in normal operation converter can’t correctly reflect the failure of another AC power grid, which is the fundamental reason for continuous commutation failure of normal operation converter and the rapid increase of DC current on the inverter side is the direct reason for the continuous commutation failure.

**Improved commutation failure predictive control strategy**

The logic of improved CFPRED control strategy is shown in Figure 6, and an improved CFPRED controller is represented in the dotted frame. The fault switching module is used to determine and quantify the situation of two AC systems, and set \( U_{dc\_fault} \) as the fault state.
variable. When the 500 kV AC bus failure, the $U_{ac\_fault}$ is 1; when the 1000 kV AC bus failure, the $U_{ac\_fault}$ is 0. In addition, when two AC grids fail at the same time, the fault switching module selects the grid with long fault time as the state output. The control strategy takes the CFPRED’s angle of the converter which connected to the fault AC network as the CFPRED’s angle of the converter which connected to the normal AC network. It realizes the control target of normal operation without commutation failure and avoids DC power oscillation.

**SIMULATION VERIFICATION**

**Calculation condition**

Based on the parameter of XT ± 800kV UHVDC engineering, the electromagnetic transient simulation model of the actual control system is established at PSCAD/EMTDC. The value of the two sides AC grid is shown in Table 1. In the calculation, the constant power control and the modified constant $\gamma$ control are adopted on the rectifier side of the UHVDC transmission system, and the UHVDC bipolar transmission power is 10000 MW.

<table>
<thead>
<tr>
<th>AC system</th>
<th>Rated voltage (kV)</th>
<th>Equivalent impedance (Ω)</th>
<th>Short-circuit current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier</td>
<td>530</td>
<td>0.191+j4.853</td>
<td>63</td>
</tr>
<tr>
<td>Inverter</td>
<td>520</td>
<td>0.498+j4.738</td>
<td>63</td>
</tr>
<tr>
<td>Inverter</td>
<td>1050</td>
<td>1.005+j9.569</td>
<td>63</td>
</tr>
</tbody>
</table>
Analysis of simulation results

Figure 7. Waveform of traditional CFPRED control.

Figure 8. Waveform of improved CFPRED control.
The 1000 kV AC bus connected to the low voltage converter on the inverter side has a metal three-phase grounding fault, which is recovered after 100 ms, and the 500 kV AC bus connected to the high voltage converter is running normally. The traditional CFPRED control waveform is shown in Figure 7. At the time of t_1, the 1000 kV AC bus had a metal three-phase grounding fault. The commutation failure occurs in the low voltage converter. The function of the CFPRED detects the fault of the AC system, and the α of the low voltage converter was greatly reduced. The 1000 kV AC bus fault has little influence on the 500 kV AC bus. The increment angle produced by the CFPRED function in the high voltage converter is very small, and the α basically maintains the angle before the failure. From t_1 to t_2, due to the increase of DC current, the commutation margin of the high voltage converter is reducing, and the high voltage converter appears multiple commutation failure. At the time of t_3, the AC fault disappears, and the DC voltage and DC current begin to recover. From t_4 to t_5, multiple commutation failure appears in high voltage converter again. At the time of t_6, the DC voltage and DC current begin to recover again. At the time of t_7, the DC power is restored to normal.

The improved CFPRED control waveform is shown in Figure 8. At the time of t_1, the 1000 kV AC bus has three-phase metal grounding fault. The fault switching module detects AC system fault, and sent increment angle of low voltage converter to high voltage converter. From t_1 to t_2, the high voltage converter doesn’t occur commutation failure. At the time of t_3, the AC fault disappears, and the DC voltage begin to recover. At the time of t_7, the DC power is restored to normal.

The DC transmission power under the two different control strategies is shown in Figure 9. It can be seen that the improved CFPRED control strategy has better dynamic performance: at the beginning time of the failure, the DC transmission power drops slowly; after the fault of the AC system, the DC transmission power recovers faster. In addition, the DC system has only one commutation failure due to the fault of the AC system, which avoids continuous commutation failure.

![Figure 9. Comparison of DC power between two control strategies.](image)

**CONCLUSION**

Based on the XT ± 800kV UHVDC transmission project, the system control strategy of the UHVDC with split connection in the inverter side is analyzed in this paper, and the simulation model with PSCAD is established, such as the voltage balance between high voltage converter and low voltage converter, TCC control and reactive power control, are analyzed and modeled in this paper. An improved CFPRED control strategy is proposed to ensure the converter commutate successfully which connected to the normal AC grid during the fault of another AC grid. The simulation results show that the improved control strategy can ensure the safe and stable operation of UHVDC System.
REFERENCES