Simulation of Grid Paralleling Devices based on back to back VSC-HVDC Converted into UPFC

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Abstract. The back-to-back VSC-HVDC paralleling device structure is similar to the unified power flow controller (UPFC) circuit structure. After completing paralleling operation, the back-to-back VSC-HVDC paralleling device can be converted into the UPFC device through relevant electrical operations. Aiming at the problem of power and frequency fluctuation in the process of conversion, a method of using circuit breaker and switch state as characteristic signals to block or open the signal of parallel side and series side converter is proposed. By this method, a smooth transition from back-to-back VSC-HVDC paralleling device to UPFC device is realized. The method is verified by PSCAD/EMTDC simulation.

1. Introduction

The flexible alternative current transmission system has a strong adaptability when the power transmission system changes or the operation mode changes. It brings an unprecedented opportunity to maintain the stability of the power system, control the power flow of the power grid and ensure the transmission capacity, which has caused many scholars to study. Therefore, the FACTS device is added to the existing AC transmission system to develop in parallel with the existing AC transmission system. The reference [1, 2] proposed a synchronous parallel method based on power transfer. Active power and reactive power are transferred through back-to-back converter to change the frequency and voltage of the system to be parallel. When the voltage difference and frequency difference meet the condition, then using the slip cross zero to complete the paralleling operation. Reference [3], the back-to-back converters were converted to other topologies after paralleling operation to expand the functions of the paralleling compound devices. Reference [4], the back-to-back voltage source converter were converted to the united power flow controller (UPFC) after grid-connection. However, fluctuations of power and voltage occurred in the conversion process, and the functions of the UPFC were verified in the paper. As the most promising FACTS device, UPFC can independently control the voltage, impedance and transmission angle of the line, and can also selectively control the active power and reactive power flow on the line. Combined with the characteristics of the UPFC structure, the paralleling device is idle for most of the time. A new control strategy is proposed to realize the integrated function of paralleling and UPFC. After the paralleling device completed the paralleling operation, the shunt and series converters are blocked. Then the paralleling device is converted into UPFC circuits through corresponding circuit operations. The control strategy is changed to realize the function of UPFC, and the fluctuation of power and voltage in the conversion process is disappeared, so that the same device can give full play to its maximum economic benefits.
2. Circuit conversion between paralleling device and UPFC device

Reference [5], a capacity-matched series transformer and multiple circuit breakers and disconnecting switches such as breakers 3QF and 4QF, the disconnection switches 5GK, 6GK and the series transformer 3BT are added to the back-to-back VSC-HVDC paralleling device, as shown in Figure 1. The control of UPFC and its equivalent model have been studied widely[6-8], including DC voltage control, AC voltage control, line current regulation, and start control.

As shown in Figure 1, when the system is in a state to parallel, all circuit breakers and switches except the breaker 4QF are off state. When the paralleling device needs to be synchronous paralleling, the circuit breakers 1QF, 2QF, 4QF and 1GK are off state, but the circuit breaker 3QF and the switches 5GK and 6GK are on state. The device completes the paralleling operation in corresponding control strategy, then the circuit breaker QF is off. The off state of the circuit breaker QF is used as the blocking signal of the converter on the shunt side and the series side. Then the circuit breaker 2QF and the switch 1GK are on state, the transformer 2BT exits. 3QF, 5GK, 6GK switch off to connect series transformer into the system. At this moment the series transformer is in the bypass state. Finally the UPFC device is realized by jumping off 4QF. The state of circuit breaker 4QF is taken as a control signal to change the control strategy. The parallel control of the UPFC is switched to realize the control of the node voltage and the DC voltage, and then the series control of is switched to realize the power flow adjustment function.

![Fig.1 Principle diagram of paralleling device circuit convertering to UPFC circuit](image1)

![Fig.2 Voltage vector](image2)

3. UPFC line power flow control principle

The active power can be transformed through the DC bus from the shunt converter to the series converter. The UPFC has much more flexible than the SSSC to control the active and reactive power of the line. In contrast to SSSC, where the injection voltage Vs is constrained to be orthogonal to line current I, the injection voltage Vf has any angle relative to the line current. If the magnitude of the injection voltage Vf remains constant and its phase angle compared with V1 changes from 0 degrees to 360 degrees, the end trajectory of the vector V2 (V2 = V1 + Vs) is a circle as shown in figure 2. As phase angle of Vs changes, the phase difference between the two bus voltages V2 and V3 also changes. Therefore, the active power P and the reactive power Q transmitted over a line can be controlled.

\[ V1 = V1 \angle 0^\circ, \quad V3 = V3 \angle \theta_3, \quad Vf = Vf \angle \theta_f \] line reactance is X. The resistance of the UPFC accesses line is ignored. Then, the active power P and the reactive power Q of the line are obtained as follows:

\[ P = \frac{V1 Vf \sin(\theta_f - \theta_3)}{X} - \frac{V1 Vf \sin(\theta_f)}{X} \] (1)

\[ Q = \frac{V1^2}{X} + \frac{V3^2}{X} + \frac{2V1 Vf \cos(\theta_f)}{X} - \frac{V1 Vf \cos(\theta_3)}{X} - \frac{V3 Vf \cos(\theta_f - \theta_3)}{X} \] (2)

Assume \( \dot{V}1 = 1.05 \angle 0^\circ, \quad \dot{V}3 = 1.03 \angle -10^\circ, \quad X = 1.0 \text{ p.u.}, \quad 0.01 \leq Vf \leq 0.1. \) According to the equations (1) and (2), the magnitude of the injection voltage is changed in steps of 0.01 p.u., and the phase of the
injection voltage is changed from 0 to 360 degrees. Then the power operation point can be obtained as shown in figure 3. It can be seen from the figure that a \( V_s \) corresponds the only one line power operating point. Therefore given the output voltage of the series side of the UPFC, the line power can be uniquely determined. Therefore, the UPFC function is verified in the subsequent simulation, the control of the line compensation voltage is realized by controlling the active component and the reactive component of the series voltage.

![Fig. 3 Power characteristics at the head of the line](image)

**4. converter control strategy**

**4.1. shunt converter control strategy**

The converter is the core equipment of the whole system. The parallel side converter operates in the rectification mode and the series converter operates in the inverter mode. The control modes of the converter are mainly divided into two categories: Control of active components and control of reactive components [9]. In the paralleling mode, the control mode of the shunt converter are fixed active power and fixed reactive power control. In UPFC mode, the shunt converter can be equivalent to a parallel current source, which works by absorbing controllable current from the transmission line. The current can be divided in two parts: one is that the active current component is used to maintain the stability of the DC capacitor, and provide the required active power for the series side converter. The other part is the reactive current component which can provide reactive compensation to maintain the stability of the node voltage. Based on the above functions, the control strategy of the shunt converter is shown in Figure 4.

![Fig.4 shunt converter control block diagram](image)

**4.2 series-side converter control strategy**

The series converter mainly maintains the DC voltage and regulates the reactive power in the paralleling mode. The series part of the UPFC mainly consists of a series converter and a series transformer. UPFC device changes the line power flow by controlling the voltage of the series injected into the grid, including the amplitude and phase of the voltage. It is impossible to change the power flow of line transmission by changing the power output of the converter. Because corresponding to the UPFC injection power surface the output voltage is not unique. Thus the control strategy of the series converter should use current control strategy. The instantaneous power theory is used to calculate the
given command of the line current from the given line transmission power command. According to the transformer ratio relationship between the line current and the converter output current, the reference value of the output current of the converter can be calculated. The state feedback cross-decoupling method is used to realize current decoupling control[10]. The control strategy of the series side converter is shown in Figure 5.

Switching control of the shunt side and the series side, the state of the circuit breaker is used as the trigger control of the mode switching. The state of each electrical switches in the three modes are shown in Table1, closed state is ‘0’ and open state is ‘1’. The characteristic state is extracted according to each switch state in each mode. The characteristic state of the grid-connected mode to the conversion mode is the closed state of the circuit breaker QF, that is the "0" state. The characteristic state of the conversion mode to the UPFC mode is the open state of the circuit breaker 4QF, that is the "1" state. The state of the circuit breaker QF under conversion mode and UPFC mode are all in the closed state. Therefore the closed state of breaker QF and the closed state of 4QF "AND" is taken as the control signal of the blocking series-parallel converter. The open state of the circuit breaker 4QF is used as a control signal from the conversion mode to the UPFC mode.

| modes       | QF | 1QF | 2QF | 3QF | 4QF | 5GK | 6GK | 1GK |
|-------------|----|-----|-----|-----|-----|-----|-----|-----|
| Splitting mode | 1  | 0   | 0   | 1   | 0   | 1   | 1   | 0   |
| Conversion mode | 0  | 0   | 1   | 0   | 0   | 0   | 0   | 1   |
| UPFC mode    | 0  | 0   | 1   | 0   | 1   | 0   | 0   | 1   |

5. Simulation experiment and analysis

5.1 Grid-connected model is converted to UPFC mode simulation

The simulation main topology of the grid-connected mode to the UPFC mode is shown in Figure 6. Among them, HG1 and HG2 represent System 1 and System 2, which both contain a generator with a capacity of 120 MVA and an output voltage of 13.8 kV. The generator is connected to the substation through a step-up transformer with a transformer ratio of 13.8 kv/121 kV and a double circuit line of 30km. The difference between turbine and governor of System 1 and System 2 is respectively $\omega_{ref} = 1.2$ and $\omega_{ref} = 0.9$. The loads on both sides of the system are $S_1 = 45 + j27 MW$ and $S_2 = 75 + j54 MW$. As shown in Fig. 8, the active power P of the system 1 and the system 2 are: 52.65 MW and 73.35 MW, when the system completes paralleling operation at 107s. After the completion of the grid connection, the shunt side and the series side converters are locked. At the same time BRK2 is open. BRK and BRK3 are always in the normally closed state to provide buffer for the UPFC and charge time for the capacitor on the DC side. At 145s, the parallel circuit is converted to the UPFC circuit by the corresponding circuit operation. The specific operation is that the state of BRK6 and BRK7 is switched from the off to the closed. At 150s, BRK5 is switched from the closed state to the open state, and the reactive power Q from system 1 and system 2 are 49.46 Mvar and 55.80 Mvar.
Fig. 6  Synchronization paralleling system converter into UPFC simulation model

(a) Frequency difference between two systems  (b) Phase angle difference between the two systems

(c) Voltage difference between the two systems  (d) Reactive power output between the two systems

Fig. 7  Simulation results of influence on system converting synchronization mode to UPFC

From the simulation results shown in Figure 7, it can be seen that the power output of the two systems is stable and without fluctuation, when the device switches to UPFC at 150s. The frequency of the system will fluctuate at 0.02 Hz and recover to stable value of 50Hz after about 10s. The frequency difference is attenuated to 0Hz by 0.005Hz fluctuations after 0.5s. The phase angle difference remains same before and after switching. The system voltage on both sides changed from 113.1kV before switching to 113.74kV and 112.39 kV. The voltage difference rises from 0kV before conversion to
1.35kV. The operation of the entire electrical equipment has little impact on the system and the system is basically in a stable state. The voltage difference is caused by the impedance of the series transformer on the tie line. The simulation results verify that it is feasible to switch the paralleling device to UPFC device by circuit operation after the grid-connected device is blocked.

5.2 Simulation experiment of unified power flow controller function

The circuit structure of UPFC in the PSCAD/EMTDC simulation environment is shown in Figure 8. The parameters of system S1 and system S2 are basically consistent with those of the system to be parallel in the grid-connected mode. The parallel part of the UPFC is connected to the bus of the system in parallel through a transformer. The primary side of the UPFC parallel side transformer is 110kV. The secondary side is 2kV. The capacity is 100 MVA and the leakage reactance is 0.1 p.u. DC side capacitor is \( C = 5000 \mu \text{F} \) and DC side voltage is \( U_{dc} = 4 \text{kV} \). The equivalent loss resistance of the parallel side converter is 0.001 \( \Omega \) and the inductance is 0.0005 H. The conversion ratio of the UPFC series side to the system coupling transformer is 1:1. The leakage reactance is 0.105 p.u. and the capacity is 50 MVA. The equivalent loss resistance of the series side converter is 0.001 \( \Omega \) and the inductance is 0.0005 H.

5.2.1 Simulation of system voltage regulation

The basic control objective of UPFC parallel side is to maintain the DC side capacitor voltage constant and provide reactive power to the system. The bus voltage stability of parallel access point is maintained by injecting reactive power into the system through parallel transformer. The parallel converter absorbs the active power from the grid, provides active power to the series side converter and compensates for the active loss of the circuit device, which avoids the system collapse caused by the DC capacitor voltage drop. Figure 9 (a) shows the simulation results of UPFC for bus voltage (P.u.) regulation at access points. During the simulation, the voltage reference value of the parallel side bus is changed from 1.05 p.u. at the previous moment to 1.03 p.u. and the voltage is stable at 1.03 p.u. after about 0.2 s. Figure 9 (b) illustrates the adjustment of the DC side voltage follow-up reference value when the given value of the DC-side capacitor voltage is set to 3.5 kV and the reference value of the DC-side capacitor voltage is changed to 4.0 kV at 1.5 s, which verifies the basic functions of the parallel side of the UPFC.

5.2.2 Simulation of line voltage compensation

From Figure 10 (a), it can be seen that the output voltage of series transformer increases at 2.5 s and 3.0 s due to the change of active component of line compensation voltage in 2.5 s and the step of reactive component of line compensation voltage in 3.0 s, which indicates that the voltage of series transformer can be controlled. The active and reactive components of the line compensation voltage are shown in Figure 10 (b) and (c). Because decoupling control is added to the control strategy, the interaction between the active and reactive components of the line compensation voltage is less affected. During the active component and reactive component adjustment of the line compensation voltage...
voltage, the voltage of the parallel side bus remains stable, while the voltage on the DC side has a small disturbance when the active and reactive components jump, but it quickly restores stability.

![Series transformer output voltage](image1)

![Active voltage](image2)

![Reactive voltage](image3)

**Fig. 10** UPFC compensation line voltage

6. Conclusion

In this paper, the closing state of the parallel circuit breaker and the closing state of the series transformer bypass switch "AND" is taken as the control signal of the blocking series-parallel converter, after the system completed paralleling operation. While the opening state of the series transformer bypass switch is used alone as a control signal of mode switching. It solves the long-term fluctuations of power and voltage during the conversion from the back-to-back VSC-HVDC paralleling device to the UPFC device, and adjusts the line voltage after converting into the UPFC device to change the line current. The model of the paralleling device into the UPFC device is built on the simulation software PSCAD/EMTDC, The simulation results verify the feasibility of this method.

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