Research summary of the reactive power control on the receiving-end converter station of Yazhong-Jiangxi ±800kV ultra-high voltage direct current transmission project

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Abstract. Yazhong-Jiangxi ±800 kV ultra-high voltage direct current (UHVDC) project applies the new mode of hierarchical accessing technology to significantly improve the voltage stability of receiving-end transmission system by virtue of the reactive power property of converter station. This paper studied the reactive power control by hierarchical accessing, started with the reactive power configuration of reactive power compensation device of the converter station with focus on the technology and innovation thinking of dynamic reactive power and static reactive power control, then proposed some suggestion on the direction of future research and served as reference for follow-up production and researches.

1. Introduction
Long distance transmission of ultra-high voltage direct current (UHVDC) plays an important role in new energy delivery [1]. With the increasing DC transmission capacity and intensifying DC placement, the existing DC access mode is no longer conducive to the evacuation of AC system current flow and may possibly lead to a number of problems in voltage support. To this point, the Chinese scholars have proposed a new mode to connect the UHVDC with AC grid by hierarchical accessing technology, and discussed about the advantages of this mode in improving the voltage support capability of the receiving-end system and guiding the reasonable distribution of current flow. At home and abroad, there have been in-depth studies on the planning, operation properties, reliability, placement selection and parameter setting of hierarchical accessing to the DC transmission system [2-3]. The reactive power control of ultra-high voltage converter station plays a vital role in ensuring the stable and reliable operation of AC and DC system. In accordance with the planning of 500kV grid and ultra-high voltage grid of Jiangxi province, Yazhong-Jiangxi DC project applies UHVDC hierarchical accessing mode, e.g., to access the Nanchang converter station (10,000MW) to 500kV and 1,000kV AC grid through two electrodes with 50% power of the converter station respectively. The stable operation of DC transmission system requires sufficient voltage support of the receiving-end system, and the DC control mode, DC power transmission level and intensity of receiving-end system will all influence the voltage stability of converter bus [4-7]. In order to ensure the reactive power balance of AC and DC system after the project operation both in normal condition or in the case of accident, it is necessary to study the reactive power control of Yazhong-Jiangxi DC receiving-end converter station (Figure 1).
This paper studied the reactive power control of UHVDC converter station by analyzing widely the sources of frontier researches, and put forward an integrated conclusion in terms of reactive power configuration, dynamic reactive power control, static reactive power control and steady-state reactive power control, and coordination control.

2. Reactive power configuration

The reactive power compensation device of converter station is applicable to all DC operation modes through grouping switch. The grouping capacity of reactive power compensation device should be optimized by considering the factors of switch impact, voltage control, filter performance and equipment layout. The capacity analysis of reactive grouping can be reviewed and determined by the stability calculation of transient voltage and steady-state voltage fluctuation, and meanwhile, the economic indicators should be considered. The voltage configuration, neutral grounding form and capacity configuration of low-voltage side reactive compensation device in the converter station should consider the coordinated operation of the current and ensure the normal operation of the low-voltage side reactive compensation device in the converter station. The the voltage configuration, neutral ground and capacity configuration of the reactive power compensation device at low voltage side of converter station should consider the coordinated operation of current, so as to ensure the normal operation of the reactive power compensation device at low-voltage side of converter station.

Considering the future large-scale integration of wind power into grid and the access of converter station to AC system, there will be low-voltage risk for Jiangxi grid. To prevent such risk, the voltage stability of the AC power grid in the adjacent area of converter station should be improved, the voltage fluctuation of converter bus caused by switching filter should be reduced, the static var compensator (SVC) and static synchronous compensator (STATCOM) should be installed at the low-voltage side of converter station, and the configuration of the group filter capacity should be optimized.

The reactive power consumption of the converter station is related to the factors of DC transmission power, DC voltage, DC current, commutation angle and commutation reactance. The calculation of reactive power consumption should consider the equipment manufacturing tolerance, error caused by system measurement and control, and other factors, so as to achieve the maximum reactive power consumption of the converter station. The maximum reactive power consumption under rated operation mode was listed in Table.1 (the equipment manufacturing tolerance and control error were considered).

![Figure 1. Distribution diagram of Nanchang converter station.](image-url)
Table 1. Maximum reactive power consumption of Nanchang converter station.

| DC power /GW | Electrode end | Short-circuit impedance % | Reactive power consumption/Mvar |
|--------------|---------------|---------------------------|-------------------------------|
| 10           | High-end      | 20                        | 3026                          |
|              | Low-end       | 20                        | 3029                          |
|              | Total         |                           | 6055                          |

Large-capacity phase modifier, as reactive power generation device, has unique advantages in improving the short-circuit ratio of the receiving-end AC grid, enhancing the DC transmission limit power, and ameliorating the strength and flexibility of grid. In the case of voltage reduction caused by failure at the near-end of AC grid or the commutation failure of converter valve, large-capacity phase modifier can support the stability of voltage and system by forced excitation and save more time for removing the failures. The key parameters of large-capacity phase modifier influential to the reactive power support ability can be determined by systematic simulation research and comprehensive consideration. The failure of phase switching can be effectively prevented by enhancing the voltage support capability under the same failure through selecting the appropriate configuration of excitation control system[8-9], see Table 2 for the detailed parameters.

Table 2. The dynamic reactive power parameters influential to phase modifier.

| Project                                      | Indicator                        |
|----------------------------------------------|----------------------------------|
| Direct-axis transient time constant Td’      | <0.95s                           |
| Direct-axis super-transient reactance Xd”    | <0.14                            |
| Rotor voltage forced excitation times        | 3.5 times (<0.8Un)               |
| Rotor power forced excitation times          | 2.5 times (≥15s)                 |
| Stator over-current times                    | 1.5 times (≥60s)                 |

3. Dynamic reactive control

Great endeavor has been made to improve the transient voltage stability of grid operation. Relevant researches show that the dynamic voltage stability of the whole system can be improved by significantly increasing the critical clearing time (CCT) through identifying the weak link of the transient voltage of power grid by testing the voltage stability limit and installing dynamic reactive power compensation device.

There is dynamic difference between reactive power consumption of the converter station inverter and reactive power output of capacitive compensator, such difference can make the inverter station work as dynamic reactive power source, and the inverter station can input dynamic reactive power to AC grid after the DC active power fall back, so as to improve the voltage stability of receiving-end grid and avoid load shedding.

The hybrid reactive power compensation should be taken into consideration when the hierarchical access converter station and the ultra-high AC system share the same station. The studies relating to the simulation test on the over-voltage amplitude and frequency characteristics of the unloaded closure of the front and rear UHV transmission lines with hybrid reactive compensation have provided the analytical and theoretical bases for selecting the optimized parameters and configuration methods of UHV hybrid reactive compensation[10-11].

Energy-storage static synchronous compensator can effectively restrict the power oscillation of UHV AC lines when improving the voltage stability of the receiving-end power grid with AC/DC hybrid system, and thus significantly enhancing the operation safety and stability of the AC/DC hybrid system in the manner of multiple targets control on the stability of this system.

The reduction of effective short-circuit ratio of multiple-infeed DC placement power grid is related to the transient instability of major fault. Therefore, to strengthen the network frame and increase the
number of phase modifiers can enhance the power grid intensity and improve the stability of reactive power voltage of the DC inverter station. In addition, the stability of reactive power voltage of the multiple-infeed AC/DC hybrid power grid can also be reasonably ameliorated by reinforcing the weak link of multiple-infeed power grid (namely its effective short-circuit ratio) in combination with practical engineering application.

In combination of the integrated control requirements for reactive voltage of converter station and the difference of excitation control strategy between phase modifier and normal generator unit, the configuration and parameter setting of the main excitation control ring and main excitation limiting function of the phase modifier were analyzed with a view to improving the capability of phase modifier to adjust and support the reactive voltage in transient process. The accurate simulation analysis and the key parameters influential to the dynamic reactive voltage support in the case of major faults during UHV AC transmission can provide key basis for adjusting and setting the parameters of phase modifier and voltage regulator.

Phase modifier can enhance the static voltage stability margins of the system, raise the minimum voltage of the system during failure, reduce the probability of DC system commutation failure and narrow down the scope of AC system faults that may cause the DC system commutation failure. This paper studied on the dynamic reactive power characteristics of the DC inverter station with the DC inverter, capacitive filter and reactive power compensator as main components and the DC inverter station used as the large-capacity dynamic reactive power source of the receiving-end grid. In terms of the DC receiving-end grid with voltage stability a dominant instability form, this paper proposed the criteria of activation and revocation as well as the control strategies for DC emergency control with the HV bus voltage of DC inverter station as characteristic quantity.

4. Steady-state reactive power control

When setting the upper and lower limits for the integrated reactive power and voltage control strategy of conventional substation, the influences caused by the change of operation modes were not considered, therefore, it might be difficult to regulate reactive power and voltage due to the limited regulation capacity of the station in certain operation modes. In addition, it is impossible for such control strategy to consider the coordination relation between the voltage and reactive power during regulation, so it is easy to see the repeated oscillation of system operation points in the adjacent abnormal area after the operation of voltage regulating equipment. Any measures about voltage regulation, such as increasing the reactive power or installing a set of low capacitance influential to voltage and reactive power, would be adopted for the purpose of improving the partition map of the integrated control on voltage and reactive power of the steady-state reactive power control of UHV converter station, so as to ensure the trajectory of the system operation points on the voltage-reactive power plane would be always parallel to the VQ change vector corresponding to the voltage regulation measures, and there would be no opposite voltage regulation measures in the adjacent area. In this way, there would be no more than two measures used to ensure the system operation points enter into normal area and thus effectively avoiding the oscillation in adjacent area caused by repeated use of opposite voltage regulation measures.

In terms of the currently adopted tertiary voltage control mode of Automatic Voltage Control (AVC), the optimal voltage value of the substation bus along UHV lines was calculated by the global reactive power optimization of the tertiary voltage control. The secondary control is the partitioned decoupling control which can calculate the power plant control strategy of each partition according to the targets set by the tertiary voltage control.

In terms of the UHV transmission compensation mode, the configuration of fixed high resistance compensation combined with the groups of low-capacitance and low-reactance can flexibly control switching, and then the reactive power compensation for UHV ride-through reactive power can access to the 100kV side of the UHV station. Through appropriate configuration of the low-capacitance and low-reactance groups, the impacts caused by UHV ride-through reactive power on 500kV grid can be minimized by the switching of low-capacitance and low-reactance groups during the system operation.
The reactive power control of the UHV DC transmission should not only meet the basic filter requirements for system operation, but also consider the boundary conditions of AC voltage and reactive power exchange. Generally, there are several types of reactive power control, such as absolute minimum filter control, maximum/minimum voltage control, maximum reactive power exchange control, minimum filter control and reactive power exchange control/voltage control. When reducing the probability of commutation failure, the priority of the above-mentioned reactive power control types should be considered.

Currently, the low-capacitance/low-reactance switching of the UHV substation has not yet been integrated into the control scope of the AVC system in the adjacent area of UHV AC. In the case of inappropriate switching of low-capacitance/low-reactance groups, AVC system can merely control the 500 kV power plant in the adjacent area of UHV, so it can hardly control voltage and may cause the inappropriate flow of reactive current. Therefore, the low-capacitance/low-reactance switching strategy of UHV substation and the coordination and cooperation of AVC system should be regarded as the next research direction.

5. Coordination control

5.1. Coordinated control of equipment
In the high voltage DC system with weak strength of AC system and frequent fluctuation of DC transmission power at infeed-end, the coordinated control of the reactive compensation device of the converter station can significantly enhance the voltage stability of converter bus. The relevant researches indicate that by comparing the voltage stability of converter bus when the strength of infeed AC system is different, it can be analyzed that bus voltage instability is easy to occur when switching the DC power fluctuation and capacitor bank in converter station connected with weak AC system. Then the multi-mode coordinated control strategy for reactive power compensation device in converter station connected with weak AC system can be designed in line with the proposed multi-target required for the reactive power control on converter station and on the basis of the STATCOM multi-mode control strategy and the control strategy engaged in AVC regulation. It mainly includes the steady-state voltage regulation mode for converter bus voltage without static tracking rated voltage, the automatic voltage control mode for converter station engaging in the voltage regulation of the AC system in the adjacent area, and the transient control mode for restricting the voltage fluctuation and commutation failure in the event of short-circuit fault of converter bus.

5.2. Coordinated control of control methods
The calculation of the reactive power compensation capacity of UHV substation can determine the reactive power control targets and analyze the relation of transmission-end and receiving-end voltage by considering the active transmission characteristics in the mode of substation constant voltage control, and thus providing guidance for planning, designing, operating and scheduling the substation active power compensation.

The overvoltage level of UHV AC bus in converter station is mainly affected by the DC running condition. DC can run stably after disturbance and the overvoltage level is not high. Analysis shows that in the event of DC block after disturbance, it may cause relatively high overvoltage, but the operating overvoltage of UHV converter bus can be effectively reduced by using lightning rod with low rated voltage.

In terms of DC infeed receiving-end grid, it’s important to avoid commutation failure and maintain voltage stability. Great attention should be paid to the prediction control of commutation failure and the impacts of prediction parameters on the nonlinear reactive power trajectory of the inverter station and voltage stability. The voltage stability of receiving-end grid can be enhanced by improving the prediction parameter optimization measures of the large disturbance reactive power demand characteristics of inverter station.
When DC system is running, the AC bus limit voltage control is always effective whether the reactive power control mode is in power mode (Q) or voltage mode (U). The frequent AC filter switching of converter station should consider that whether the voltage evaluation logic of the reactive power control function of DC station control system is reasonable, so as to avoid the instability of control system in DC station.

5.3. Hierarchical access
The DC system with hierarchical accessing is different with the traditional DC single-layer accessing no matter in topological structure or control mode, so in order to ensure the safe and stable operation of AC/DC system, it is urgent to conduct a comprehensive study on the characteristics of receiving-end hybrid system with new mode of DC accessing. When the bus voltage at each layer of the receiving-end with hierarchical accessing is stable, the voltage stability ordering under different control modes can be obtained by analyzing the difference of voltage stability under different DC control modes.

There is electrical coupling relation between the AC/DC systems of UHVDC hierarchical access mode, between the high and low converter valves and between the receiving-end AC systems with two layers of different voltage levels, which makes the problem of system reactive power regulation and voltage stability more complicated. The static voltage stability of the converter bus can be enhanced by reducing the impedance of receiving-end AC system, equivalent contact impedance of AC system and DC system transmission power, or increasing the turn-off angle, in addition, the static voltage stability of the converter bus will also be impacted by the equivalent impedance angle of the receiving-end AC system.

Considering the coupling effect of high-end and low-end converters, the study on the interaction mechanism of reactive voltage in hierarchical system can be conducted under different DC control modes to analyze the interaction mechanism and influencing factors of reactive voltage in hybrid system. By comparing and analyzing the advantages and disadvantages of different control modes based on the difference of influencing factors and the size of reactive power fluctuations, the study proposed a hybrid coordinated control mode targeted for receiving-end hybrid system and applicable for the grid with “strong DC and weak AC”. The analysis and simulation verification on the reactive power characteristics of hybrid system under different control modes indicates that, when the high-end and low-end of converter side adopt the same control mode, the reactive power external characteristics of hybrid system shows a similar change rule; when the high-end and low-end of converter side adopt the extinction angle control mode, the range of reactive power fluctuation after disturbance is relatively small but may impact the AC voltage stability; and when the high-end and low-end of converter side adopt the voltage control mode, the fluctuation rage of reactive power and extinction angle is relatively large but the reactive power external characteristics of hybrid system is conducive to maintain receiving-end voltage stability. Therefore, according to the comprehensive analysis of the advantages and disadvantages of different control modes, it can be concluded that the hybrid coordinated control mode of reactive power in hybrid system is more conducive to maintain the stable operation of hybrid system with hierarchical accessing [12-13].

The power transmission level of DC system will affect the voltage stability of converter bus at each layer. The higher the DC transmission power is, the weaker the voltage stability of converter bus at each layer would be. Take the DC constant current control, constant voltage control and constant extinction angle control as the basic control modes, and then analyze the impacts on voltage stability of converter bus exerted by the power output characteristics of converter at each layer under different control combinations, voltage stability characteristics of converter bus at 500kV layer and 1000kV layer, as well as the different DC power transmission levels. The analysis shows that under the control mode of constant power on rectifier side and constant extinction angle at high-end and low-end inverter, when the receiving-end system is weak and the DC transmission power is relatively high, small reactive disturbance may lead to voltage instability of converter bus at each layer.
6. Conclusions
Reactive power control of UHV converter stations becomes so important that researches in this field are badly in need. This paper reviews the research status at home and abroad from the four aspects such as reactive power configuration, dynamic reactive power control, steady-state reactive power control and coordinated control of the converter station, and tries to give suggestions for subsequent research. We expect this paper will play a certain reference to this field and Nanchang Power Converter Stations.

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