A Back-to-back VSC-HVDC System of Yu-E Power Transmission Lines to Improve Cross-region Capacity

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***Abstract*—With the rapid development of hydropower in the southwest of China, the energy transmitted by ultra high voltage direct current (UHVDC) is ever increasing. At the same time, the power grid continues to expand westward, creating a service area. The stability of the Southwest China Power Grid is becoming a major issue. It is necessary to coordinate the development of hydropower and the construction of cross-region interconnections to optimize the grid structure. The Yu-E denotes the connection between the two region Yu (Chongqing) and E (Hubei) in China. The Yu-E project is a back-to-back voltage source converter based high voltage direct current (VSC-HVDC) project designed to realize an asynchronous connection of the Southwest and Central China Power Grids. The project will improve the bi-directional power support capability and optimize the grid structure. In addition, the Yu-E project will improve hydropower cross-region transmission capacity and enable the Southwest China Power Grid to utilize the power from the Three Gorges in the Central China Power Grid. In this paper, the fault isolation, low-frequency oscillation, sub-synchronous oscillation and short-circuit level are investigated and analyzed. Meanwhile, the impact of the Yu-E project on AC systems is studied in detail. In the end, the overall system design of the Yu-E project is introduced. The research results show that the Yu-E project can increase the transmission capability of the Southwest and Central China Power Grids, and enhance the stability of asynchronously interconnected AC systems. At the same time, the Yu-E project also serves as a demonstration project for the future development and application of VSC technology for the world.**

***Index Terms*—Additional control, asynchronous interconnection, back-to-back, system design, VSC-HVDC.**

I. Introduction

THE Southwest China Power Grid is connected to the North China– Central China Power Grids synchronously through two 1000 kV Changzhi- Nanyang- Jingmen ultra high voltage alternating current (UHVAC) lines and four 500 kV AC transmission lines. In order to ensure the long-distance large-scale cross-regional hydropower transmission from Sichuan, three $\pm$ 800 kV ultra high voltage direct current (UHVDC) transmission projects (i.e., Xiangjiaba to Shanghai, Jinping to Sunan and Xiluodu to Zhejiang) have been constructed and the asynchronous interconnection between the Southwest and East China Power Grids has been achieved. In addition, the 4th UHVDC project will be commissioned in 2019.

With the rapid development of hydropower in the southwest region, the number of UHVDC transmission projects has increased. At the same time, the power grid has continued to extend westward increasing the service area. The stability of the Southwest China Power Grid is becoming a major issue. In particular, the transmission power of UHVDC is relatively large; the scenario where a large DC system is feeding into a weak AC network has occurred. Under this scenario, the UHVDC commutation failure caused by the AC faults in the East China Power Grid could lead to a power surplus at the sending end, which is a major threat to the stability of the Southwest China Power Grid. Except for the hydropower, that is either consumed locally or delivered to the East China Power Grid through UHVDC, the remaining hydropower is primarily transmitted to the Central China Power Grid through the Sichuan-Chongqing AC tie lines. During summer, when all the hydropower stations are operating and connected into the system, the maximum power that can be delivered from Chongqing to Hubei is only 2,800 MW, which fails to fully utilize all the hydropower. At the same time, the thermal limits, transient stability and dynamic stability problems, such as short-circuit level, power transmission capability, system oscillation, etc. are becoming more and more prominent. If some severe faults occur in the Southwest Power China Grid, the large-scale power flow re-distribution in the Sichuan-Chongqing section may lead to out of step splitting and exert a negative impact on the hydropower delivery of the Sichuan Power Grid. Therefore, it is necessary to coordinate the development of hydropower stations and construction cross-region interconnections to optimize the grid structure.

Voltage source converter based high voltage direct current (VSC-HVDC) has significant technical advantages in cross-regional weak grid interconnection and renewable energy integration [1]–[3]. It has many benefits such as rapid control of active and reactive power, fast reversal of power flow, flexible

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operational modes, etc. [4], [5]. In addition, by implementing a proper control strategy, VSC is capable of increasing system damping and suppressing potential oscillations [6]. When the fault occurs in the AC grid, the active and reactive power delivered by the VSC station can be adjusted through emergency control measures to reduce the impact of the fault on the system [7]–[13]. All these advantages of VSC can provide good solutions to the challenges raised in the Southwest and Central China Power Grids. The State Grid Corporation of China has planned to construct the Yu-E project. As shown in Fig. 1, the Yu-E project has two channels, which are the northern channel and southern channel (the southern route is from Chongqing Zhangjiaba to Hubei Enshi; the northern route is from Chongqing Jiupan to Hubei Longquan). Each channel has two $\pm$ 420 kV/1250 MW back-to-back monopole VSC HVDC links. When the project is commissioned, the existing two 500 kV AC links will be replaced, and the Southwest and Central China Grids will become asynchronous interconnections, which will further optimize the cross-region grid structure to export more hydropower and improve the bi-directional power support capability of the system.

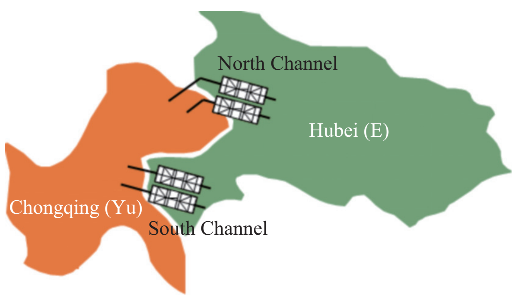


Fig. 1. Geographical schematic of the Yu-E back to back VSC HVDC project.

This paper first analyzes the stability problems of the Southwest and Central synchronous power grids and the impact of the Yu-E project is studied. Second, in order to enhance the Yu-E project's supporting capability to the AC system, as well as to reduce the risks in system safety and stability, an additional control strategy is proposed. Then through the developed electro-mechanical and electro-magnetic transient simulation models, it is verified that the Yu-E project with the proposed additional control strategy can improve the system's stability significantly. In the end, the overall system design of the Yu-E project is introduced.

II. Optimization of the Grid Structure

At present, when the Southwest and Central China Girds are synchronously interconnected, if there are faults such as commutation failures occurring on any of the three UHVDC projects (Xiangjiaba- Shanghai, Jinping- Sunan and Xiluodu-Zhejiang), these faults could result in around 5,000 MW power oscillation and significant voltage drop in the AC tie lines, which will lead to the disconnection of tie lines and out-of-step splitting. Mono-polar or bipolar blocking of any of these UHVDCs will lead to disturbances propagating along the AC tie lines to the Central China Power Grid, which will result in the generators in the Three Gorges becoming unstable.

To solve the aforementioned problems, VSC-HVDC can be used to isolate AC system faults, to avoid the impact of power flow re-distribution on the Three Gorges generators and to transmit Sichuan hydropower by HVDC to central and east China. The schematic diagram of the Yu-E project is shown in Fig. 2.

In order to verify the effect of VSC-HVDC on enhancing the system stability, first, a simulation model of the Yu-E project is developed using electro-mechanical transient software PSASP (detailed parameters will be provided in section 4 of this paper). Based on the assumption that the data for the short-circuit level of the Southwest and Central China Power Grids is the average value during summer in 2016, the analysis for the DC blocking faults of three UHVDC projects is performed with two scenarios considered: synchronous interconnection through AC tie lines and asynchronous interconnection through VSC HVDC, respectively. The system data

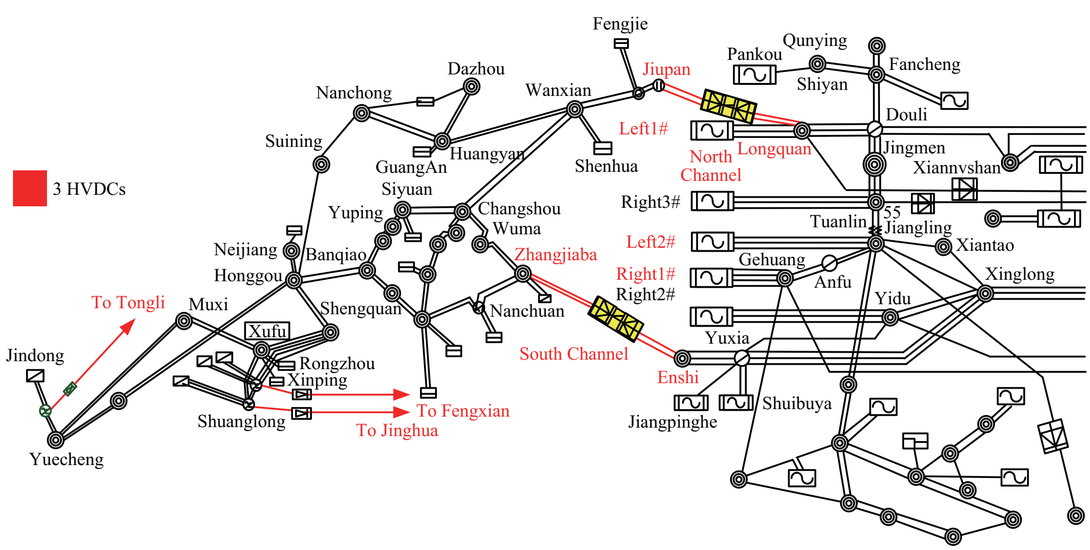


Fig. 2. Yu-E VSC-HVDC system connection diagram.

are: power from Chongqing to Hubei through the northern route is 2,000 MW, power from Chongqing to Hubei through the southern route is 900 MW. Left 1#, Left 2# and Right 1# generators of the Three Gorges contributing 6,080 MW, 4,560 MW and 4,560 MW respectively; power transmitted from Longquan to Douli is 4,500 MW; the power delivered by Jinsu, Fufeng and Binjin UHVDC projects are 7,200 WM, 6,400 MW and 8,000 MW respectively.

The Jinsu UHVDC project is used as an example to compare the responses of the synchronous and VSC asynchronous interconnections. Fig. 3 (a) and (b) show the power angle of the Three Gorges generators after a bipolar block fault of the Jinsu UHVDC with and without VSC. Fig. 3 (c) shows active and reactive power of the single-circuit AC tie lines of the southern route on the Yu-E section without VSC connection. Fig. 3 (d) shows the active and reactive power fed into the AC system from the single-pole of the southern route on the Hubei-side VSC station.

Based on the simulation results, as shown in Fig. 3 (d), when the fault occurs at 10 s, the power angle of the Three Gorges generators is kept stable, as the constant power control implemented in the VSC-HVDC can isolate the fault effectively. Consequently, the impact of the Jinsu UHVDC blocking faults on the Central China and East China Power Grids could be reduced, which improves the flexibility of grid operation.

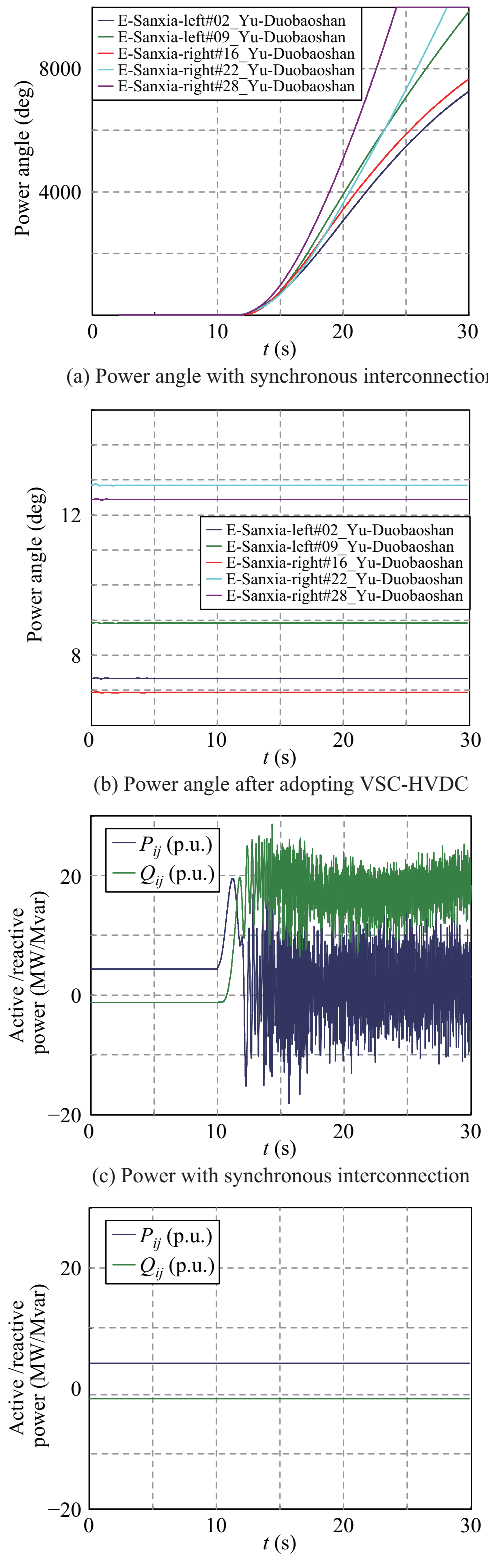
III. Enhancing System Stability

When the Southwest and Central China Power Grids are synchronously interconnected, they are connected to the Hubei Power Grid through the double-circuit AC tie lines of northern and southern AC tie lines. The system is then connected to the North China Power Grid by the Hubei-Henan interconnection and 1,000 kV AC tie lines. The whole system forms a chain-type grid structure, which will limit the cross-region hydropower delivery from southwest China. In the following sections, the dynamic stability is studied from the aspects of low-frequency oscillation and Sub-synchronous Oscillation (SSO). The back-to-back VSC-HVDC technology and the corresponding control strategies such as additional frequency/additional damping control is adopted to suppress low-frequency oscillation and reduce SSO risk in order to enhance system stability [14]–[16].

A. Increasing the Damping and Suppressing Low Frequency Oscillation

Under the synchronous interconnection operation mode, significant negative damping provided by the main hydro-governor of the Southwest China Grid in some frequency bands could easily lead to ultra-low frequency oscillation. For example, when the commutation failure occurs and causes the LCC converters to block in the aforementioned three UHVDC systems, this may lead to ultra-low frequency oscillation in the Southwest China Grid and the system may incur out-of-step splitting.

When the VSC-HVDC is employed to achieve asynchronous interconnection, under the aforementioned operational modes and fault conditions, additional control strategies could be implemented by modifying the outer control loop of the VSC control system, which will provide rapid regulation of DC power and thus could suppress the low-frequency oscillation and increase the system damping.



(a) Power angle with synchronous interconnection

(b) Power angle after adopting VSC-HVDC

(c) Power with synchronous interconnection

(d) Power after adopting VSC-HVDC

Fig. 3. Comparisons of power angle and power stability before and after adopting VSC-HVDC.

The above VSC-HVDC functions are verified by the following simulations. Under the operational modes of the short-circuit level of the Southwest and Central China Grids, the average value of the 2016 winter normal load situation, various AC line faults and the converter blocking faults caused by UHVDC commutation failure are simulated. Simulation results show that when the commutation failure and DC interlock fault occur in three UHVDC systems of Fufeng, Jinsu and Binjin simultaneously, it will result in ultra-low frequency oscillation of the Southwest China Power Grid, as shown in Fig. 4. The oscillation frequency is about 0.055 Hz.

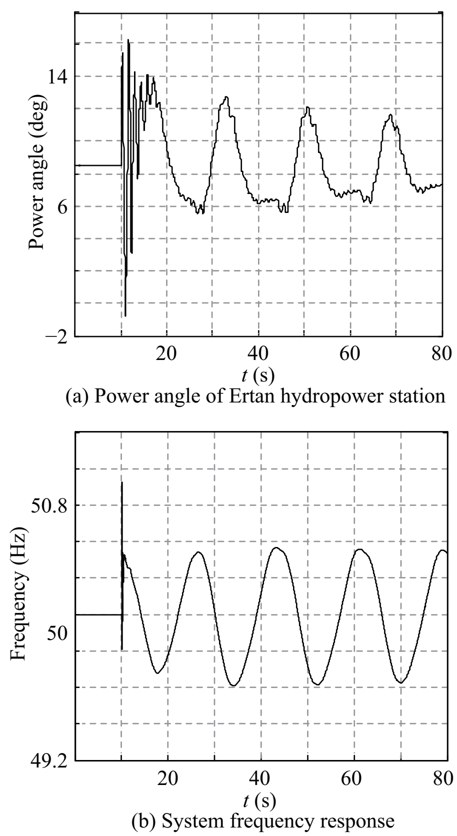


Fig. 4. System responses after the commutation failures.

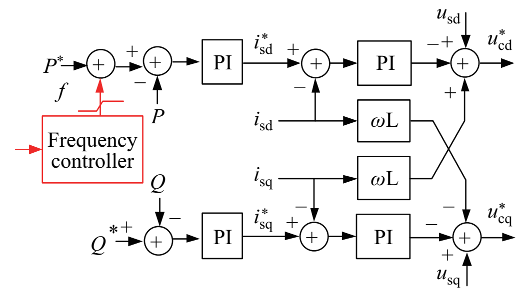


Fig. 5. Schematic diagram of additional control strategy.

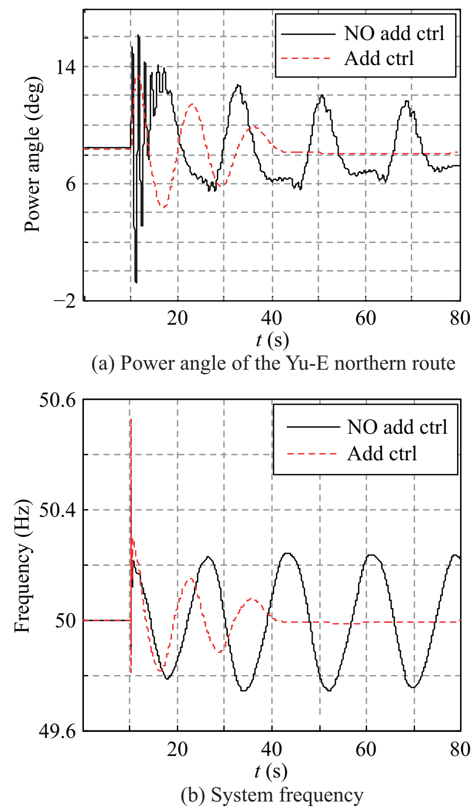


Fig. 6. System frequency responses after frequency support control is activated.

When the VSC is used to interconnect different AC networks, the frequency signal will be adopted as the input for the additional control. When the frequency of the PCC fluctuates, the reference value of the outer active power control loop will be modified correspondingly. Based on the operational mode, the over-current and over-voltage characteristics of the device, the upper limit for the outer power loop signal is set to be 500 MW. The control strategy is shown in Fig. 5 P^* and P are the reference and measurement of active power. Q^* and Q are the reference and measurement of reactive power. Through the outer power loop and inner current loop control, the voltage reference value u^*_{cd} and u^*_{cq} can be obtained.

As shown in Fig. 6, after adopting the additional control strategy, the damping of the low-frequency oscillation will increase and the frequency will recover to 50 Hz 30 s after the fault. The ultra-low frequency oscillation caused by the commutation failure of the converters in the three UHVDC projects of the Southwest Power Grid is effectively suppressed in two oscillation periods, restoring to its pre-fault status.

B. Reducing Risks of SSO

Henglu and Shenhua power plants are close to the Fengjie series compensation station. The series compensation station is connected to the northern VSC HVDC channel, as shown in Fig. 7.

By using the complex torque coefficient method, the complex torque coefficient curve of the generators in the synchronous interconnection system is analyzed. It can be seen that Henglu, Shenhua and other power plants in the northeast of Chongqing are exposed to SSO risks under a synchronous interconnection scenario (the green line), as shown in the first curve in Fig. 8.

However, when the Yu-E Project is adopted to achieve an asynchronous interconnection, even if no additional damping

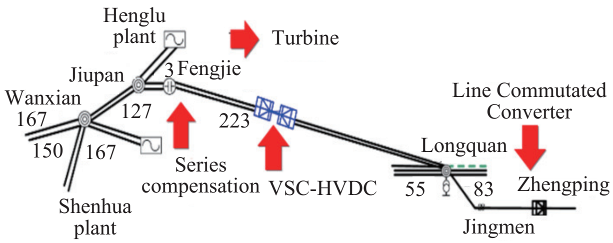


Fig. 7. Geographical diagram of region which is close to the Fengjie power plant.

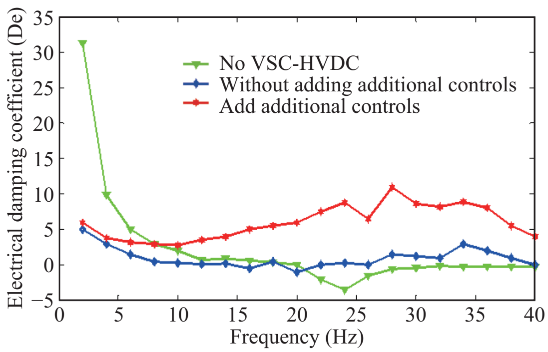


Fig. 8. Comparisons of system damping characteristics.

control strategy is implemented for VSC, this can reduce the SSO risks caused by the series compensation units. However the overall damping coefficient of the system can still be improved.

In order to further suppress the SSO, the SSO suppression control strategy could be implemented in the control of VSC. It adopts the hybrid damping control method to suppress SSO, which are configured separately for the constant reactive and active power regulation of VSC to damp the SSO, as shown in Fig. 9. The comparison of system damping characteristics is shown in Fig. 8. After the SSO suppression strategies are added into VSC, the overall electrical damping coefficient of the system is further improved, and they are all positive damping. Consequently, the SSO risks caused by series compensation units could be reduced. The simulation results also show that if the SSO occurs between the Henglu power plant and the AC system outside VSC, the SSO could be suppressed by VSC. The active and reactive power based SSO suppression strategies could be employed and the torsional vibration of the shaft system can be suppressed. Therefore, a suppression strategy which combines active and reactive power regulation could be adopted in actual VSC projects.

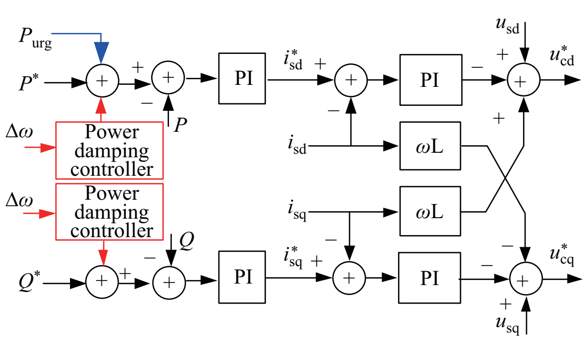


Fig. 9. SSO suppression strategy.

IV. Reducing the Short-Circuit Level Near the Three Gorges Region

Due to the location of power stations being highly concentrated and requiring a strong grid structure, the short-circuit level near Three Gorges region is always relatively high. Under a synchronous interconnection, the short-circuit levels at the extra-high voltage stations such as Douli and Jiangling. etc are high.

When an asynchronous interconnection through the VSC is employed, due to the fault isolation of VSC, the Southwest China Power Grid will not feed the short-circuit current to the Central China Power Grid. The short-circuit levels of the relevant stations which are close to Three Gorges will be reduced. The short-circuit level has been calculated under a 2016 summer normal load situation, and are shown in Table I and Table II. It can be seen from these two tables that the short-circuit levels of the 500 kV bus-bars in Hubei, Sichuan and Chongqing are all decreased, and the drops of the short-circuit levels in Enshi, Yuxia and Jiupan are more than 40%. Under these operational modes, the short-circuit levels are lower than the case when all the hydropower stations are operating and connected into the system. All the short-circuit currents are kept within the rating of the existing AC breakers.

TABLE I
Short-Circuit Current of 500 kV System in Hubei Province (Unit: kA)

500 kV busbar	Synchronous interconnection	VSC-HVDC asynchronous interconnection	Variation	Absolute value (%)
Enshi	22.39	13.29	−9.1	40.64%
Longquan	39.46	32.33	−7.13	18.07%
Yuxia	22.38	13.29	−9.09	40.62%
Douli	52.31	48.91	−3.4	6.50%
Jingmen	14.54	14.54	0	0.00%
Xinglong	43.54	41.66	−1.88	4.32%
Tuanlin	46.25	44.72	−1.53	3.31%
Yidu	24.50	23.48	−1.02	4.16%
Jiangling	52.58	51.88	−0.7	1.33%

TABLE II
Short-Circuit Current of 500 kV System in Chongqing Province (Unit: kA)

500 kV busbar	Original synchronous interconnection	VSC-HVDC asynchronous interconnection	Change value	Absolute value of the percentage
Jiupan	23.48	12.51	−10.97	46.72%
Wanxian	30.09	24.89	−5.2	17.28%
Huangyan	27.32	26.62	−0.7	2.56%
Changshou	40.15	37.36	−2.79	6.95%
Siyuan	33.95	32.84	−1.11	3.27%
Ba'nan	35.70	34.06	−1.64	4.59%
Banqiao	37.98	37.26	−0.72	1.90%
Zhangjiaba	32.28	25.44	−6.84	21.19%

V. SYSTEM DESIGN

A. System Design of the System

The capacity of the system needs to match with the power capacity of the nearby AC system. The transmission capacity of the Yu-E project depends on the transmission capacity of the southern and northern channels. For the southern channel, under the conditions of ambient temperature being 40°C, conductor temperature rise being 80°C and power factor being 0.9, the thermal limit of a single-circuit line is 2,750 MW. For the northern channel, under the same conditions of ambient temperature and conductor temperature rise, and power factor being 0.95, the thermal limit is determined to be be 2,400 to 2,550 MW [17].

Taking the above transmission capacity requirements into consideration, two parallel VSC-HVDC back-to-back systems each rated at 2,500 MW, are designed for each channel. Due to the capacity limitation of the VSC-HVDC, each channel is composed of two parallel 1,250 MW back-to-back VSC-HVDC links (as shown in Fig. 10).

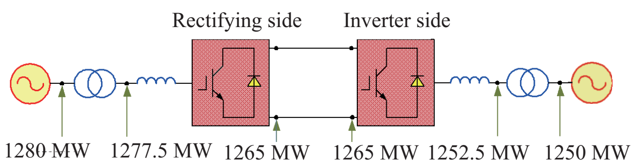


Fig. 10. Schematic diagram of the converter capacity design.

Considering the power losses of the converters, transformers and other equipment, in order to enable the inverter side active power to be 1,250 MW, the active power at PCC of the rectifier side should be 1,280 MW. Taking into account the power factor requirement of 0.925, the overall system capacity should be 1,390 MVA.

The power range in which the VSC-HVDC can operate is represented by a PQ diagram. Its operating constraints include current limits, power angle characteristics, limitation of modulation index and sub-module voltage fluctuations [17], [18]. Considering the above constraints, the proposed PQ diagram is shown in Fig. 11.

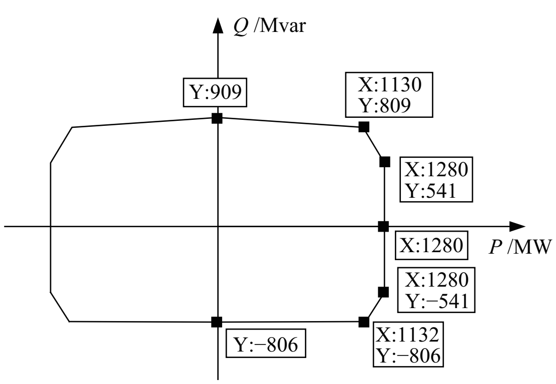


Fig. 11. PQ diagram of the converter.

As can be seen from Fig. 11, the rated power of the converter is 1,280 MW/ ± 541 Mvar, and the maximum reactive power that the converter can provide is 909 Mvar.

B. Main Circuit of the System

Each back-to-back link has a symmetrical monopole structure. The converter adopts the modular Multi-level Converter (MMC) topology and is rated at ± 420 kV/1,390 MVA.

The interface transformer has a Y0/Yn/Δ winding. During normal operations, there is no DC voltage bias on the converter side of the transformer. To avoid using of additional grounding equipment, the VSC system is grounded through a large resistance Rg which is connected to the neutral point of the converter side of the transformer. The main circuit diagram of the Yu-E project is shown in Fig. 12.

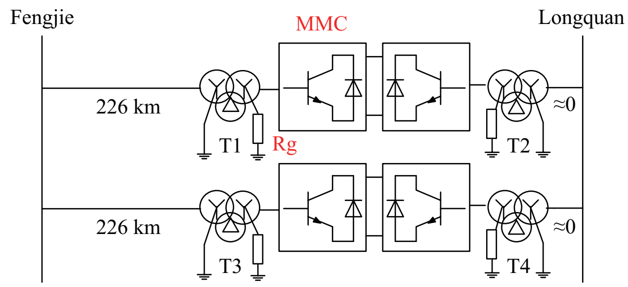


Fig. 12. Main circuit diagram of the Yu-E system (Northern Channel).

C. Main Circuit Parameter Design

The main circuit parameter design is primarily used to determine the main parameters of the converter valve, arm reactor, transformer, starting resistor and other primary equipment. Under the condition of meeting the system performance requirements, the selection of relevant parameters needs to achieve the optimal performance in both technical and economic aspects [19]–[21].

According to the operating characteristics of the system and the converter designed capacity, the detailed parameters of the converter can be calculated as shown in Table III.

TABLE III
NOMINAL PARAMETERS OF THE CONVERTER

Parameter	Nominal value
DC Voltage/kV	± 420
Arm current (RMS)/A	1021
Arm current (Peak)/A	1757
SM capacitor voltage/V	1680
Number of SMs per arm (including redundancy)	540

Since the RMS value of the converter arm current is 1,021 A, the 3,300 V/1,500 A type IGBTs with a long-term operating current which is equal to or greater than 1,200 A are chosen. Considering the system operational mode and over-voltage protection design, the rated voltage of each sub-module in the converter is determined to be 1,680 V. Consequently, 500 sub-modules are required to maintain the normal operating voltage of the converter. Considering an 8% redundant design, the number of sub-modules per arm of the converter is designed to be 540. The 5 layers the valve tower is designed as shown in Fig. 13.

The capacity of the interface transformer is generally the transmission capacity of the system. But due to the excessive capacity, the transformer used in this system generally needs

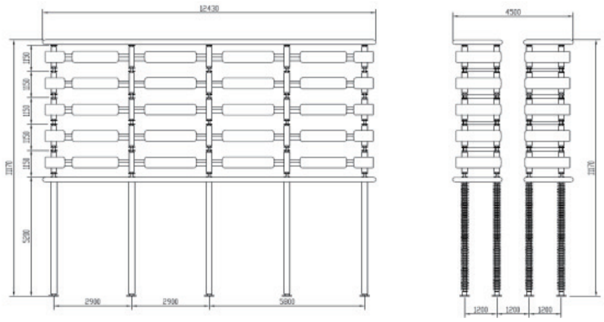


Fig. 13. Schematic diagram of the valve tower of the Yu-E project.

to be three single-phase transformers. In addition, one spare transformer is required. Based on the actual transformer design, the leakage inductance of the transformer is generally 0.14 p.u. to 0.16 p.u.. When determining the tap range of the transformer, in addition to the voltage range of the AC system and the requirement of reactive power exchange between the converter station and the AC system, the maximum and minimum DC voltage level, modulation strategy and other aspects should also be considered. It should be noted that the voltage on the secondary side of the transformer should not be too low, otherwise the current flowing through the converter will be too high; this voltage should also not be too high, or the reactive power that the converter could provide will be limited. The main parameters of the interface transformers designed in Yu-E project are shown in Table IV.

TABLE IV
MAIN PARAMETERS OF THE CONVERTER TRANSFORMERS

Type	Single phase, three-winding, oil-immersion
Cooling method	Oil directed air force (ODAF)
Rated Power	465MVA/465MVA/150MVA
Rated line voltage	525 kV/420 kV/35 kV
Leakage reactance/%	14
Rated line current	1534A/1918A/7423A
Short circuit impedance	$U_{12} = 15\%$, $U_{23} = 9\%$, $U_{13} = 26\%$
Winding type	Ynyd
Rated frequency	50 Hz
Valve side neutral point resistance	15 kΩ, Steady state current 1A, Transient current 28A

The minimum value of the arm inductance depends on the fault current limitation under extreme fault conditions, e.g., DC side pole-to-pole faults. The lower limit of the arm reactors can be determined by considering the protection speed and fault current withstanding capability of the converter; the upper limit of the arm reactors depends on the system dynamic performance, power transmission requirements, cost, footprint and other factors. According to the design requirements of the Yu-E project, the main parameters for arm reactors are shown in Table V.

TABLE V
ARM REACTOR PARAMETERS

Parameter	Value
Arm inductance	80 mH
Type	Air-core dry type
Cooling method	Natural air cooling
Current	DC: 508A + AC: 955A

D. Starting Resistor Design

When the VSC-HVDC transmission system starts up, it needs to limit the starting current to ensure the safety of the converter and other equipment. The parameters of the starting resistor need to be determined according to the system simulation of the startup process. The parameters of the starting resistor need to ensure that the charging current is limited to a certain range. In addition, it needs to ensure that its impact energy withstand capability can meet the system requirements.

In the design of the Yu-E project, the starting charging current should not exceed 50% of the rated current, and the charging time should also be limited. The starting resistor of the Yu-E project is selected to be 10 kΩ, and the peak current can be 42.86A during the startup process. The starting resistor parameters of the Yu-E project are shown in Table VI.

TABLE VI
MAIN PARAMETERS OF THE STARTING RESISTOR

Item	Parameter
Resistance	10 kΩ
Starting peak current	42.86 A
Energy withstand capability	10 MJ
Cooling method	Natural air cooling

VI. CONCLUSION

The Yu-E project realized the asynchronous interconnections between the Southwest and Central China Power Grids. From the aspects of fault isolation, system stability and short-circuit level, the scenarios of before and after of the Yu-E project implementation have been analyzed and compared in this paper, respectively. The influences of the Yu-E project on the AC network are studied in great detail. Meanwhile, several additional control strategies have been proposed. Based on the self-developed electro-mechanical transient model for the Yu-E project, the proposed additional control strategies for low-frequency oscillation and SSO are verified. In the end, the system design for Yu-E project is introduced, which includes the main circuit design, primary equipment parameters selection, the converter valve design, etc.

With the construction of the Yu-E project, high-voltage and large-capacity VSC-HVDC interconnection technology will be further demonstrated and provide an efficient solution for future large-scale power interconnection demand in China.

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