

Transient Stability Analysis of Hu-Liao HVDC and AC Parallel Transmission System*

Peng Ye¹, Yuqiu Sui¹, Yinghua Yuan¹, Xiaoming Li¹, Jiaqi Tao²

¹Northeast Electric Power Research Institute Co. Ltd Shenyang, China; ²Northeast China Grid Company Limited Shenyang, China.
Email: yepeng_126@sina.com

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ABSTRACT

In this paper, transient stability analysis was focused on Hu-Liao HVDC and AC parallel transmission system. The Hu-Liao HVDC project was introduced; Simulation method and mathematic models of AC and DC systems were studied as well as corresponding regulators and controllers. The dynamic performance and the interaction between AC and DC systems during serious disturbance were researched by detail time-domain simulation. Comparison was also made under different operation schemes. The research will bring important and significant reference for further operation and stability control of Hu-Liao HVDC and AC system.

Keywords: HVDC, Transient Stability, Control Strategy, Time-Domain Simulation

1. Introduction

Since the first High Voltage Direct Current transmission project was commissioned into commercial operation in 1954, HVDC has been developed so rapidly that it has been widely applied in such fields as large power transmission over long distance, interconnecting two asynchronous systems, power transmission through submarine cables for supplying power to islands and so on. Compared with three-phase AC transmission systems, conventional HVDC is superior in the following aspects [1]: Firstly, HVDC need less cost in constructing and operating; Secondly, it needs not keep operating synchronously between the two AC systems; Thirdly, it is easy to control and adjust power flow, etc.

Among the many HVDC long transmission schemes around the world, very few operate in parallel to AC transmission of comparable capacity. Problems for parallel AC/DC operation is primarily related with the coordination between AC and DC power flows and how each system reacts to any disturbance [2]. It is well known that AC transmission systems have the inherent means to reschedule their power flows and to provide timely and sufficient synchronizing torque to secure such flows following disturbances such as AC faults, load rejection or generator tripping, etc. How a HVDC in parallel to AC system reacts in those situations has always been a cen-

tral question, particularly for planning and daily operation of such a complex scheme. In reference [3-6], the interaction action between AC and DC parallel transmission system were studied, the theory and operation rules of such power system were demonstrated with simulation examples. Results show that HVDC schemes in parallel operation with AC transmission are prone to both transient swing angle and voltage instabilities. And the risks of instability will increase during disturbances. In reference [7-9], research on advance control strategy for a HVDC scheme in parallel operation with AC systems was discussed. By these unconventional control strategies, the HVDC scheme can actively participate in the instantaneous rescheduling of power and improve the dynamic performance of power network. In reference [10,11], a real AC and DC parallel transmission system in South China was studied from operation and control aspects.

The HuLunbeier-Liaoning (abbreviated as Hu-Liao hereinafter) HVDC project was the first AC/DC parallel transmission system in North China, which was employed to transfer electricity from Hulunbeier energy center to Liaoning province. In particular, in the sending side of HVDC, Hulunbeier has a very weak network. As a result, the stability problem in operation is very critical. It is a challenge work for the operator to keep such a special AC/DC parallel transmission system operating in an economic and secure state.

In this paper, transient stability analysis was focused

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on the Hu-Liao HVDC and AC parallel transmission system. The Hu-Liao HVDC project was introduced; Simulation method and mathematic models of AC and DC systems were studied as well as corresponding regulators and controllers. The dynamic performance and the interaction between AC and DC systems during serious disturbance were researched by detail simulation. Comparison was also made under different operation schemes. The research will bring important and significant reference for further operation and stability control of Hu-Liao HVDC and AC system.

2. Hu-Liao HVDC and AC Parallel Transmission System

Northeast China Electric Power Network System consists of four provincial networks, Liaoning, Jilin, Heilongjiang and East of Inner Mongolia. These networks have been linked with 500 kV transmission lines. And Liaoning electric network is connected with Huabei network by back-to-back HVDC links with a rated capacity of 1500 MW. **Figure 1** shows the schematic of Hu-Liao HVDC and AC parallel transmission system.

Hulunbeier is rich in coal, large scale power plants are under constructing. Liaoning province is a rapid developing province in economic but much lack of energy. So based on the mutual interest and the idea of optimizing resources, Hu-Liao HVDC project is put into operation.

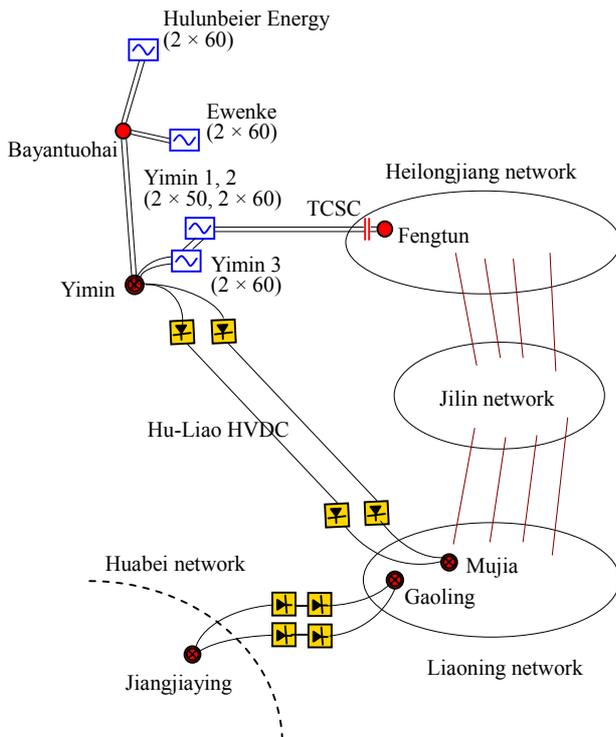


Figure 1. Schematic of Hu-Liao HVDC and AC parallel transmission system

Hu-Liao HVDC transmission is a bipolar 12-pulse HVDC transmission system with rated DC voltage ± 500 kV, rated power 3000 MW, rated current 2500 A. Overhead lines have a length of 908 km long. Yimin converter station locates at east of Inner Mongolia, which is 10 km away from Yimin power plants. It acts normally as a rectifier and its AC side rated voltage is 500 kV. Mujia converter station is in the center of Liaoning province and connected with Anshan 500 kV station with two 21 km lines. It acts principally as an inverter and its AC side rated voltage is also 500 kV. The Hu-Liao HVDC transmission system operation modes include bipolar mode, monopolar ground return mode, monopolar metallic return model and monopolar parallel line ground return model. The HVDC system can be operated under rated voltage and lower voltage. The Hu-Liao HVDC transmission normally operates in P mode (constant power control mode). I mode (constant current control mode) can be used as a back-up mode.

As mentioned above, large scale power plants are under construction in Hulunbeier. Before Hu-Liao HVDC implemented, there are two power plants, namely: Yimin 1 and 2, with altogether capacity of 2200 MW. Electric power is transferred to the west of Heilongjiang province through two 500 kV lines. At Fengtun station, Thyristor Controlled Series Compensation (TCSC) is installed to improve the transfer capability. Up to now, three new power plants, Yimin 3, Hulunber Energy and Ewenke, are set up. The electric power capacity is 3600 MW and they are mainly transferred to Liaoning province by Hu-Liao HVDC system.

There are disconnecting switches between the buses of Yimin 1, 2 and Yimin 3 power plants. When they are closed, Hu-Liao HVDC and AC system are operating in parallel. There is power exchanging through AC and DC system. Generally, when AC and DC system is operated in parallel, the fault occurred in either AC or DC system would lead to instantaneous or permanent power imbalance in power system, and quantity of power will shift through AC and DC system, which would be a great impact to transient stability. It is a challenge for system operation, especially due to such a weak delivering side.

3. Mathematic Models and Criterion in Simulation

The electromechanical transient simulation of this AC and DC hybrid system was made through PSASP. Northeast electric power network data include about 1500 buses, 330 generators and two groups of DC lines. Only 500 kV and 220 kV voltage network are considered in calculation. As PSASP offered adequate mathematics models for each type of electric elements, a majority of them are defined by PSASP according to the requirement of the simulation. Individuals are developed through user program interface such as DC and TCSC models and

controllers. The details are as follows:

3.1 Models for AC System

For most of generators, five-order model is adopted, in which the variations of E_q'' , E_d'' and E_q' are considered. They are fit for detail simulation of salient pole synchronous generators. As for the individual small hydroelectric equipment, two-order model is adopted, in which it is approximately hold that E_q' could keep constant. Most of wind turbines are modeled as doubly-fed direct-drive wind power generators. The models of the corresponding regulators such as excitation system, speed control system and PSS, are selected and defined in the software according to the practical case.

For system load, it is described as combination of fifty percent constant impedance and fifty percent induction motor during dynamic simulation. Three-order model of induction motor is used here to simulate the dynamic features of loads. The parameter of stator leakage reactance is selected as 0.18 pu.

The electric distance is relatively near between TCSC and DC lines. The Yi-Feng TCSC is composed of two parts: fixed part and variable part. The fixed part occupies thirty percent of the total transmission line capacity and the variable part occupies fifteen percent. In the dynamic process, the TCSC acts as follows: The fixed part is sure not to be bypassed when fault occurred in transmission lines; The variable part is to be bypassed when three or two phase fault occurred in the line; while when single phase fault occurred, the fault phase is bypassed and the forced compensation will take action in normal phase; The forced compensation will also take action when fault occurred in neighbor line. The bypass time of TCSC is 0.05 s after fault occurring. The control logic of the variable part is shown in **Figure 2**. Where, P and V are measured power and voltage, which is used for oscillation control; $t_{trigger}$ is the signal of beginning time and T_{forced} is the continuous time of the action. The maximum compensation capacity is forty-five percent.

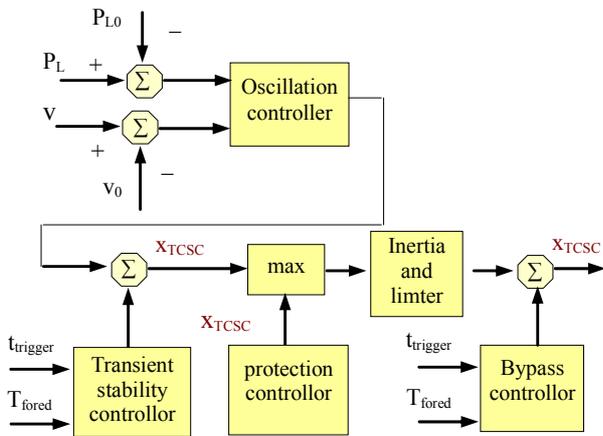


Figure 2. Control scheme of TCSC

3.2 Models for DC System

The DC model used in steady state calculation is shown as the following equation, in which approximation was made in reactive power calculation and in this way the equation form was much simplified.

$$\begin{cases} P_{ac} = U_d I_d \\ Q_{ac} = P_{ac} \tan \varphi \\ \cos \varphi \approx U_d / U_{d0} \end{cases} \quad (1)$$

where, U_{d0} is the converter transformer no-load DC voltage, P_{ac} and Q_{ac} is the active and reactive power from AC to DC. I_d and U_d is the current and voltage of DC line.

In normal operation, HVDC links required to transmit a scheduled power. In such an application, the master control layer receives the power schedule, modifies by auxiliary power control and then converts the power signal into the coordinated bi-pole current order commensurate with the DC voltage. Pole control is the core of HVDC control and activates the appropriate controller of the rectifier and inverter station according to the state of AC/DC systems. Then it produces the firing angle for both rectifier and inverter stations. The control scheme is shown in **Figure 3**.

Pole control at the rectifier side has a current controller, which takes the maximum and minimum current constraints and the VDCOL into consideration. The minimum firing angle control is embedded implicitly in the

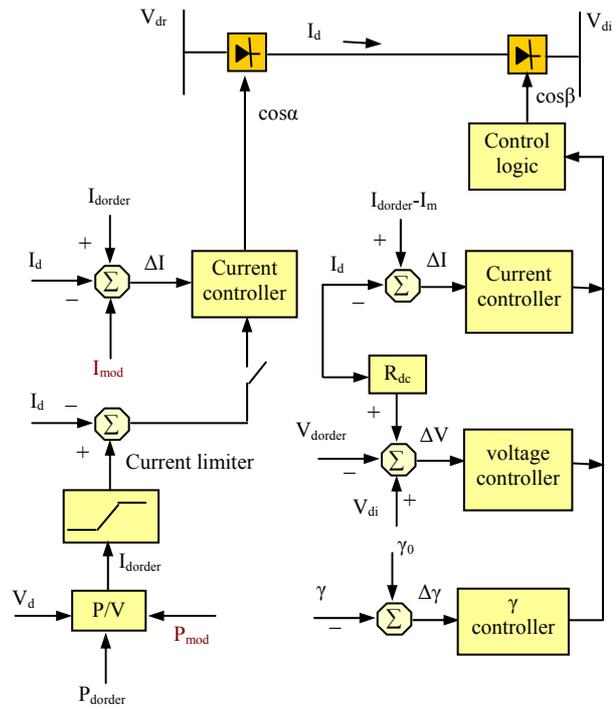


Figure 3. Control scheme of DC system

current controller by angle limits. Pole control at the inverter station includes a voltage controller, a constant current controller and a constant extinction angle controller. Current error I_m provides a transition between the current control and voltage control to facilitate control stabilization. The shift logic of these controllers is implemented by:

$$I_d = \frac{U_{d0r} \cos \alpha - U_{d0i} \cos \gamma}{d_{xr} + R_d - d_{xi}} \quad (2)$$

where: d_{xr} , d_{xi} are the equivalent resistance of the rectifier and inverter. R_d is the resistance of DC line. α and γ correspond to the rectifier ignition angle and inverter extinction angle.

When situation needed, additional control will be joined through P_{mod} or I_{mod} to fully exert the DC features of fast power control and improve the dynamic performance of AC system.

3.3 Criterion for Transient Stability

According to power system stability guideline of China, to keep transient stability, the following conditions must be satisfied at the same time:

Angle stability: after disturbance, any rotor angle between two generators in the same AC system takes on a damping oscillation.

Voltage stability: the continuous time of low voltage under 0.75 pu is within 1 s. The voltage of pivot buses is above 0.8 pu when the fault is clear.

Frequency stability: the frequency collapse will not happen with secure measures such as loads shedding and generator tripping. The frequency can restore to the normal level and the large unit operation will not be affected.

4. Transient Stability Analysis

Transient stability criterion for the studied system requires the system to be stable after clearing of any single fault or successful reclosing. Amount of simulations were done on this system. For AC system, the worst condition occurs when three phase permanent fault happens near Yimin power plants. For DC system, the worst condition occurs when bipolar blocking happens. Stability measures are necessary for most cases.

4.1 Dynamic Behavior when AC Faults

The typical case was studied when a permanent three phase fault occurred in the exit of 500 kV Yi-Feng line. The steady state condition is 6 units for DC power sending and DC capacity 3000 MW. Stability measure is that three unit tripping in Yimin plants and AC/DC separated within 150 m. Because the close electric distance with Yimin bus, AC bus voltage of Yimin converter reduced a lot and is close to zero in the fault instant. As a result, DC voltage brought down along with AC voltage till it

can not work its way and quitted temporarily. The imbalance between energy and power of AC system in Yimin and Hulunbeier areas was further increased and the instability of the system became even worse. After one second the fault line is cleared, the AC voltage is recovered. When condition is permitted, DC system restarted and DC power is restored, which is much helpful for AC system stability. Voltage, rotor angle and DC power curves during the disturbance were shown in **Figure 4**, **Figure 5** and **Figure 6**.

To study the influence of DC power to AC stability, simulation was done under 4 units and different DC power. Results were shown in **Figure 7** without measure and in **Table 1** with necessary measure. Results showed that power exchanging from AC to DC system is advantageous to improve AC system stability.

4.2 Dynamic Behavior when DC Faults

When fault occurred in DC line, the bipolar blocking is the most serious one. In this case, mass power shifts to Yi-feng lines and make a great impact on AC system. If

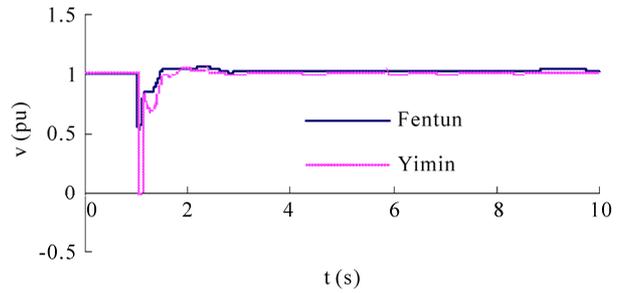


Figure 4. Voltage variation of Yimin and Fengtun bus

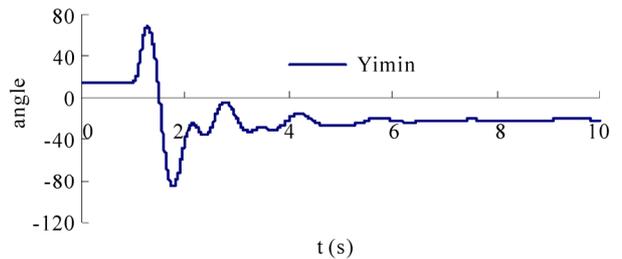


Figure 5. Rotor angle variation of Yimin unit

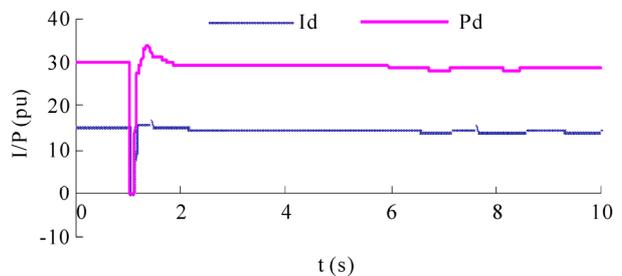


Figure 6. DC power and current variation

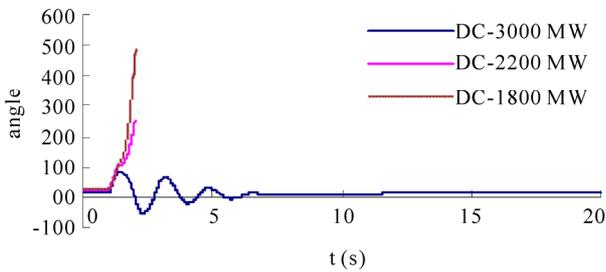


Figure 7. Rotor angle variation of Yimin unit under different DC power

Table 1. Stability measures under different DC power

DC capacity	Measures To Keep stability
3000 MW	No measures needed
2600 MW	two units tripping in Yimin plants within 150 ms
2200 MW	two units tripping in Yimin plants and AC/DC separated within 150 ms
1800 MW	and AC/DC separated within 150 ms

DC can restart successfully, the oscillation can be appeased and AC system keeps stable; Else, AC system will lose stability without secure control measures.

In the above simulation, The DC system experiences a restart failure for the first time and a success start over a lowering voltage for the second time. Along with DC restore, the AC system got a smooth resumption. To keep stability, the control measures under different DC powers are listed in the following table in case of bipolar blocking and failure restart. Results showed that the severity of the fault is closely related with the exchanging power between AC and DC system and the unit boot mode of Yimin plants.

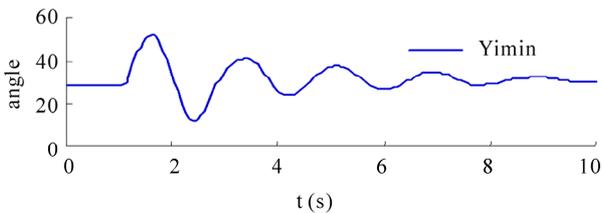


Figure 8. Rotor angle variation of Yimin unit

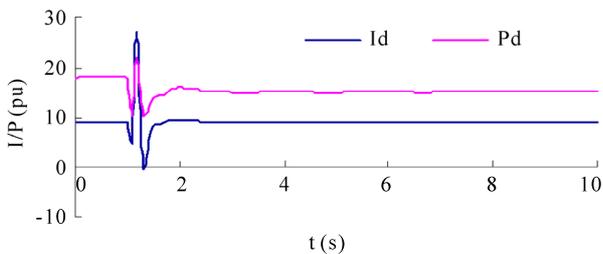


Figure 9. DC power and current variation

Table 2. Stability measures under different DC power in bipolar blocking

DC capacity	Measures to keep stability
6 unit, 3000 MW	5 units tripping
4 unit, 3000 MW	3 units tripping
4 unit, 2200 MW	2 units tripping
4 unit, 1800 MW	2 units tripping

4.3 Additional Controls for AC/DC Hybrid System

The following simulation was done in such an operation: 4 units for DC power sending and DC power 1800 MW. First, to research the features of additional controls for AC/DC hybrid system, simulations were calculated by three cases: that is no additional control, with TCSC forced compensation control and with DC emergency power control. Results were shown in Figure 10. When the additional control of TCSC and DC is activated, the transient stability can be improved but in a limit compared with unit tripping under such serious faults.

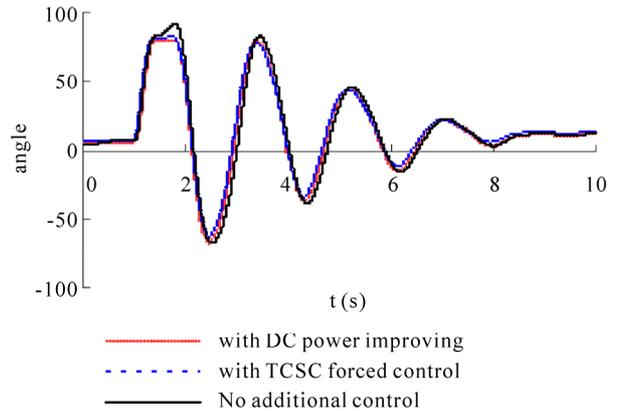


Figure 10. Additional control effect for AC and DC hybrid system

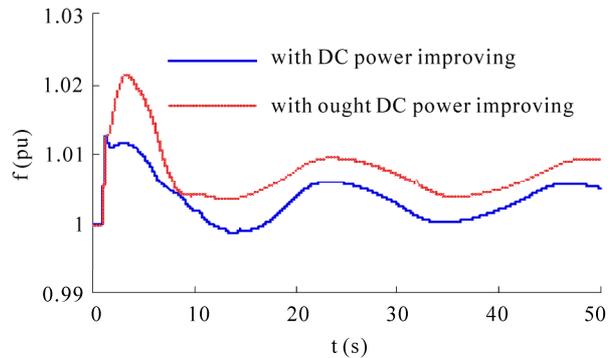


Figure 11. Ewenke frequency when AC and DC is separated

Secondly, frequency restore will meet problem when AC/DC is separated during dynamic process. It is mainly due to the AC simple structure in the rectifier side of DC system and the mismatch power between the DC system and AC islands system. The frequency simulation was done in two cases: without additional DC control and improving DC power by 15%. Results show that frequency can be recovered in an acceptable range with DC control.

The HVDC system with island generators in sending side will meet a frequency stability problem when the AC/DC parallel transmission system changed from connection into separation. Frequency stability depends on the generation capacity in the sending side and the HVDC power. Improving the generation capacity in the sending side and decreasing the mismatch power between the generation capacity and DC power in the sending side will be helpful to the improvement of frequency stability. DC emergency power control is necessary in the frequency control process. Amount of simulation has done to explore the frequency stability rules of such a special HVDC system. The results and stability terms are listed in the following table, which shows the relationship between the mismatch power and frequency stability. Advanced DC additional power controller is still needed for delicate frequency control.

5. Conclusions

In this paper, transient stability analysis was carried out focus on the Hu-Liao HVDC and AC parallel transmission system. The dynamic performance and the interaction between AC and DC systems during serious disturbance were researched by detail simulation. Only several examples are showed and discussed here as space limited. Results showed that:

1) As for the weak network of Hu-Liao rectifier side and the limit of AC transfer capacity, transient stability problem is rather serious. The dynamic interaction between AC and DC system during disturbance is intense.

2) The exchanging power between AC and DC system have a corresponding influence on dynamic performance and control strategies for keeping transient stability. Power exchanging from AC to DC system is advantageous to improve AC system stability.

3) By proper control, TCSC forced compensation and DC emergent power transfer can improve system stability. Compared with generator tripping and AC/DC separating, they are only a subsidiary control method for the researched system.

4) Frequency stability by additional DC controls is necessary when AC/DC parallel transmission system changed from connection into separation.

The research will bring important and significant reference for further operation and stability control of Hu-Liao HVDC and AC system. Further research still

Table 3. The maximum line transmission of Yimin-Yimin converter to keep frequency stability

DC island generation		Line transmission limit of Yimin-Yimin converter (MW)
Unit number	Unit generation	
4	No limit	-650 ~ 850
	> 1550	-350 ~ 850
3	< 1550	-350 ~ 550
	> 650	-350 ~ 550
2	< 650	-50 ~ 550

remained on the topics such as the optimal operation of AC and DC system, DC separated operation and control, strategies design for stability control and so on.

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