IOP Conf. Series: Materials Science and Engineering **199** (2017) 012001 doi:10.1088/1757-899X/199/1/012001

Study on the ability of Shanghai UHV AC grid access point voltage regulation

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Abstract. Shanghai as China's highest load density and largest urban power grid, located in the end position of East China Power Grid,is an important access point of East China UHV AC power grid. Making sure the voltage of UHV power grid placement has enough regulation ability is an important condition for safe operation of the system. The basic measures of system voltage regulation are given and the possible problems of voltage of UHV power grid are analyzed in the actual operation. Using sensitivity analysis method to calculate the ability of Shanghai UHV power grid placement voltage regulation after East China UHV AC target grid operation.

1. Introduction

Shanghai as China's highest load density area and largest urban power grid, located in the end position of East China Power Grid[1],is an important access point of East China UHV AC power grid.After Huainan-Shanghai-Nanjing UHV AC power transmission project put into operation, the "Anhui power to the East" engineering and Zhejiang - Fuzhou UHV AC power transmission project constitute of the end network of East China Power Grid, which will form the world's first special high-voltage AC loop network.Due to the characteristics of UHV system, such as large transmission capacity, long distance line, large charging power and reactive power severe change under different operation modes[2-7], also with the limitation of the frequency and times of the reactive power compensation equipment, it is unable to accurately track and compensate the reactive power exchange between UHV and 500 kV power system. It may exceed the capacity of the placement near zone of 500kV power network,which may cause difficulties on the grid voltage regulation[8]. Therefore, it is necessary to analyze the voltage regulation capability of the access point.

At present, the research on voltage and reactive power of UHV AC transmission system mainly focus on the influence of the grid voltage level and voltage stability after UHV AC power transmission project access to the grid[9-13], and also of the reactive power and voltage control strategy of UHV system[14-15]. This paper based on the sensitivity analysis method focuses on voltage regulation ability of Shanghai UHV power grid access point after East China UHV AC target grid put into operation.

2. Basic measure of voltage regulation

2.1. The voltage of Generator regulator

Generator providing active power also and reactive power, is the most basic reactive power control equipment in the power system,which plays a critical role in the process of establishing the normal operating voltage of the system. The reactive power transmission with long distance of generator will increase the net loss, so it is generally used to adjust the voltage of the machine or to meet the reactive power balance in the vicinity of the power plant.

2.2 Transformer regulating tap

Regulating transformer tap is the most direct way of regulating voltage, but the transformer is not a reactive power source, which neither produces reactive power, nor absorbs reactive power. Its main function is adjusting reactive power distribution and voltage level of system.Transformer includes on-load tap-changing transformer and no-load tap-changing transformer. The former is often used in the case of frequent load changes, and the latter is generally used in the case of no need to adjust the tap for a long time, such as adjusting the tap only with seasonal load change.

2.3. Low voltage reactive power compensation device

In the power system, the low voltage reactive power compensation device mainly includes shunt capacitor, reactor, static var compensator and synchronous condenserLow-voltage capacitors and reactors as common low-voltage reactive power compensation device, are usually installed in the low voltage side of transformer. In the actual operation of the system, it is generally divided into groups with transmission power change of transmission lines, to make sure the voltage of the high voltage side maintain in a reasonable range. The low voltage reactive power compensation device is widely used in the regulation of steady state voltage and power factor, because it has the advantages of easy adjustment of compensation capacity and easy setting the compensation place in the power system.

The UHV AC transmission system with large fluctuation of reactive power requries low voltage reactive power compensation device has higher capacity. But there are mainly two factors that affect the low voltage reactive compensation capacity of UHV Transformer. On the one hand, the transformer has limited capacity of low-voltage winding, on the other hand, the effect of reactive power compensation is weakened with the consumption of transformer and extra high voltage line.

Although according to the provisions of the power system and the safety guidelines:The capacity of the low-voltage winding of the transformer in the power system under ultra high voltage is less than 30% of the total capacity under normal conditions.Extra high voltage transformer has great demand for low voltage reactive power capacity, so according to the actual situation, the special high-voltage transformer can be used for the proper expansion of the low-voltage winding.For UHV power transmission lines, the method of reactive power compensation using low voltage reactive power compensation device is technically mature and feasible.

2.4. High Voltage Reactor

In order to solve the problem of voltage rise caused by excess of charging power and limiting the power frequency overvoltage in case of light load in the UHV AC transmission line, it is necessary to install large capacity compensation equipment on the transmission line, such as the large capacity high voltage reactor, but such measures will produce some negative effects:

(a) High operating voltage in small mode or low operating voltage in large mode

The power peak valley load difference in Yangtze River Delta load center is very large. The phenomenon that heavy and light load frequently alternate often appears in UHV AC transmission system, which may cause the system under-voltage with heavy load or over-voltage with light load. In order to deal with the above two kinds of situation, the usual measure is installing low voltage capacitor \ reactor group in the low-voltage side of the transformer. In economy respect, the measure is bound to cause an increase in costs due to reactive power compensation device; In the technical aspect,

IOP Conf. Series: Materials Science and Engineering **199** (2017) 012001 doi:10.1088/1757-899X/199/1/012001

the low voltage compensation will be restricted by the transformer capacity, which may not be able to meet the requirements.

(b) The transmission capacity of transmission line and the generalized natural power decrease with the increase of the compensation degree.

In the initial period of operation of UHV AC power grid, the grid system is weak. In order to make sure the safe and stable operation of the system, the UHV transmission power is light. Although the high resistance compensation is higher, the demand of reactive power for the line can be self-sufficiency; With the gradual strengthening of the UHV grid and the increase of transmission power, the line needs to absorb a large number of reactive power. The decrease of system operating voltage and the increase of reactive power transmission also led to the increase of the system network loss.

3. Sensitivity of voltage variation with node reactive power injection

Sensitivity in power system is generally refers to the sensitivity of the state variables of the system operation condition affected by the disturbance vector. In the system with n nodes, it is assumed that the node 1~m is the PQ node, the node m+1~n-1 is the PV node, and the node n is the balance node. The sensitivity equation of power flow calculation can be expressed as:

$$\begin{bmatrix}\Delta\boldsymbol{P}\\ \Delta\boldsymbol{Q}\end{bmatrix}=-\begin{bmatrix}\boldsymbol{H} & \boldsymbol{N}\\ \boldsymbol{K} & \boldsymbol{L}\end{bmatrix}\begin{bmatrix}\Delta\boldsymbol{\delta}\\ \Delta\boldsymbol{V}\end{bmatrix} \tag{1}$$

Type: ΔP, ΔQ stand for the deviation vector system active power and reactive power; Δδ stands for the phase angle of node voltage variation; ΔV stands for the deviation vector change of node voltage amplitude and its voltage amplitude ratio, the specific expression as follow:

$$\left.\begin{aligned}\Delta\boldsymbol{P}&=\left[\Delta P_1,\ \ \Delta P_2\cdots\Delta P_{n-1}\right]^T\\ \Delta\boldsymbol{Q}&=\left[\Delta Q_1,\ \ \Delta Q_2\cdots\Delta Q_m\right]^T\\ \Delta\boldsymbol{\delta}&=\left[\Delta\delta_1,\ \ \Delta\delta_2\cdots\Delta\delta_{n\text{-}1}\right]^T\\ \Delta\boldsymbol{V}&=\left[\Delta V_1/V_1,\ \ \Delta V_2/V_2\cdots\Delta V_m/V_m\right]^T\end{aligned}\right\} \tag{2}$$

Type: H, N, K, L stand for the Jacobian matrix of power flow equations; H is (n-1)*(n-1) order matrix, and the elements is $H_{ij}=\partial\Delta P_i/\partial\delta_j$; N is (n-1)*m matrices, the elements is $N_{ij}=(\partial\Delta P_i/\partial V_j)V_j$; K is m*(n-1) order matrix and the elements is $K_{ij}=\partial\Delta Q_i/\partial\delta_j$; L is m*m matrix of order, the elements is $L_{ij}=(\partial\Delta Q_i/\partial V_j)V_j$, the subscript i, j are the node number. When the active power is fixed as $\Delta\boldsymbol{P}=\boldsymbol{0}$,

$$\Delta\boldsymbol{P}=\text{-}(\boldsymbol{H}\Delta\boldsymbol{\delta}+\boldsymbol{N}\Delta\boldsymbol{V})=0 \tag{3}$$

then

$$\Delta\boldsymbol{Q}=(\boldsymbol{L}-\boldsymbol{K}\boldsymbol{H}^{-1}\boldsymbol{N})\Delta\boldsymbol{V} \tag{4}$$

In the AC high voltage power grid, the reactance of the transmission line is much larger than the resistance. The variation of active power in the system is mainly affected by the phase of voltage, and the change of reactive power is mainly affected by the change of bus voltage amplitude. In the formula (4), the numerical value of partial derivative $\partial\Delta P/\partial V$ and $\partial\Delta Q/\partial\delta$ is quite small compared with the partial derivative $\partial\Delta P/\partial\delta$ and $\partial\Delta Q/\partial V$, it is close to zero as: N≈0,K≈0, so it can be simplified as :

$$\Delta\boldsymbol{Q}=\boldsymbol{L}\Delta\boldsymbol{V} \tag{5}$$

Based on the sensitivity analysis, it is known that the variation of the voltage magnitude of the nodes in the power network is related to the deviation of the reactive power of the node, the relationship as follow:

$$\Delta \boldsymbol{Q}_D = \boldsymbol{L}_D \Delta \boldsymbol{V}_D \tag{6}$$

Assuming that the inverse matrix of JD is SD, the formula (1-3) becomes:

$$\boldsymbol{S}_D \Delta \boldsymbol{Q}_D = \Delta \boldsymbol{V}_D \tag{7}$$

Type: ΔVD stands for the column vectors of the load bus voltage magnitude deviation; ΔQD stands for corresponding reactive power deviation column vector; $\boldsymbol{S}_D$ stands for the sensitivity matrix reactive power variation of load node affected by voltage variation. And expand the equation (7):

$$\begin{bmatrix} L_{D11} & L_{D12} & \cdots & L_{D1i} & \cdots & L_{D1m} \\ L_{D21} & L_{D22} & \cdots & L_{D2i} & \cdots & L_{D2m} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ L_{Di1} & L_{Di2} & \cdots & L_{Dii} & \cdots & L_{Dim} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ L_{Dm1} & L_{Dm2} & \cdots & L_{Dmi} & \cdots & L_{Dmm} \end{bmatrix}^{-1} \begin{bmatrix} \Delta Q_{D1} \\ \Delta Q_{D2} \\ \vdots \\ \Delta Q_{Di} \\ \vdots \\ \Delta Q_{Dm} \end{bmatrix} = \begin{bmatrix} \Delta V_{D1} \\ \Delta V_{D2} \\ \vdots \\ \Delta V_{Di} \\ \vdots \\ \Delta V_{Dm} \end{bmatrix} \tag{8}$$

In the sensitivity analysis, the influence of the injected reactive power of a node to the other node voltage can be reflected by the sensitivity value of the non principal diagonal line in the sensitivity matrix.

Type: LD_{ij} stands for the sensitivity of voltage deviation of node I to the reactive power variation of node j; ΔV_{Di} stands for the voltage deviation of node I.

$$L_{Dij} = \begin{cases} V_j(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta ij) & i \neq j \\ \sum_{j=1,\, j\neq i}^{n} V_j(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) - 2V_i B_{ii} & i = j \end{cases} \tag{9}$$

Type: G_{ij} stands for the mutual conductance between nodes I and J; B_{ij} stands for the mutual admittance between nodes I and j; B_{ii} stands for the self susceptance of node I; δ_{ij} stands for angle between nodes I and J. The operating voltage of the system is in the vicinity of 1 values, and the difference of the power angle between the adjacent nodes is close to 0,and then :

$$L_{Dij} = \begin{cases} B_{ij} & i \neq j \\ \sum_{j=1,\, j\neq i}^{n} B_{ij} - 2B_{ii} & i = j \end{cases} \tag{10}$$

From the above analysis, reactive power on the voltage sensitivity and system operating state is independent, the sensitivity is only related to the network topology and the line parameters, only depending on network topology and branch reactance. It objectively reflects the various generators, reactive power compensation device for the node voltage regulation and electrical distance. Therefore, the change of the target node voltage can be analysed according to the node reactive power injection.

4. The adjustment ability of UHV power grid access point

The transformer are mostly no load voltage regulation in East China Power Grid 500kV and above voltage level, so when analyse the adjustment ability of UHV power grid access point in Shanghai AC grid after the Huainan - Nanjing - Shanghai AC UHV power transmission project put into operation, only consider the voltage regulation of the generator and the low voltage reactive power compensation device. Now we use software BPA to calculate the network nodes where the voltage regulation sensitivity of the unit and reactive power compensation device is higher in Liantang station 500kV side. The generator with higher sensitivity value is shown in Table 1, and the reactive power compensation device is shown in table 2.

Table 1. The unit with better voltage regulating effect in medium voltage side of UHV Liantang station

Unit name	Voltage per unit value / reactive power per unit value （pu/pu）	Voltage / reactive power （kV/MVar）
Hushangcao#2	0.1400	0.7256
Hujinmei#2~6	0.0016	0.0084
Huwujing#8~9	0.0016	0.0083
Huwujing #11~12	0.0016	0.0082
Hucaore#11~12	0.0016	0.0084
Hucaore #21~22	0.0016	0.0084

Note: The meaning of the sensitivity value in the table is the per unit value of the voltage variation of the controlled bus bar caused by the injected 1Mvar generator's reactive power.

Table 2. Reactive power compensation device with better reactive power and voltage sensitivity of the UHV access point

Capacitor group	Voltage per unit value / reactive power per unit value （pu/pu）	Voltage / reactive （kV/MVar）
Guoliantang#2#4	0.0021	0.0104
Huliantang#1#6	0.0015	0.0073
Husijing#1~4	0.0013	0.0065
Huxinyu#1#6	0.0011	0.0056
Hunanqiao#4	0.0010	0.0048
Hutingwei#1#3	0.0007	0.0035

Note: The meaning of the sensitivity value in the table is the per unit value of the voltage variation of the controlled bus bar caused by the injected 1Mvar generator's reactive power.

From the results in table 1 and table 2, the area where the voltage regulation sensitivity of network nodes to Shanghai UHV AC access point is higher is shown in Figure 1. The area reflects the electrical distance between the target node and control node. Therefore, we can analyse the voltage regulation ability with the reactive power resources in the region.

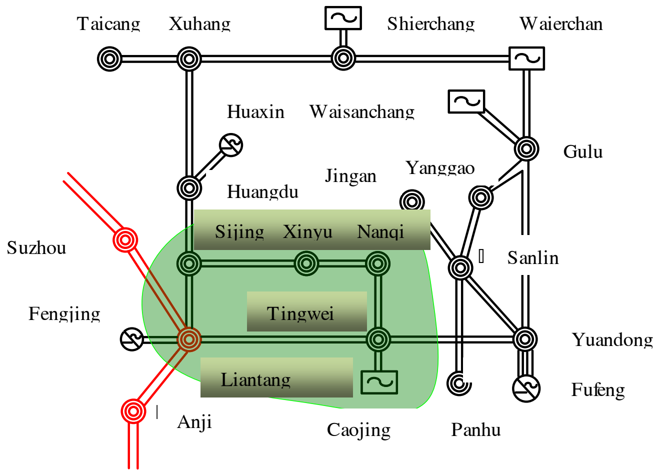

Figure 1. The area with high voltage sensitivity in Shanghai UHV AC grid

Based on the above two groups of sensitivity data, analyze the voltage regulation ability in Liantang station by different combinations of generator reactive power output and reactive power compensation device. The 3 combination methods as follow:

(1) Generator has no reactive power output amd reactive power compensation device does not cut;
(2) Generator operates with 0.98 phase lag and reactive power compensation device does not cut;
(3) Generator operates with 0.98 phase lag and all reactive power compensation device operate;

BPA software is used to simulate the above 3 kinds of situations, the capacity of generator unit output and reactive power compensation device is shown in table 3. By calculating the above three types of reactive power output simulation, the voltage values of medium voltage side in UHV Liantang station were 491kV, 497kV, 526kV. The amplitude of the voltage fluctuation can reach 35kV, and the allowable deviation of the power supply voltage in the power quality is: Sum of the absolute value of positive and negative deviations in 35KV and above is less than 10%[16]. Therefore, the voltage regulation capability of UHV access point's medium voltage side of can meet the quality requirements.

Table 3. The voltage adjustable range of Liantang station 500kV bus （kV/MW/MVar）

	The unit Participated in the mediation	Active power	Reactive power	Active power compensation station	Reactive power compensation station	Voltage of access point
Way 1	Jinmei#2~4	50	0	Guoliantang/Huliantang/Sijing/Xinyu/Nanqiao/Tingwei	0	491
	Jinmei #5~6	100	0			
	Shangcao#2	900	0			
	Wujing#8~9,#11~12	200	0			
	Caore#12, 22	50	0			
	Caore #11,	200	0			

	21					
Way 2	Jinmei #2~4	50	10	Guoliantang/ Huliantang/Sijing/Xinyu/ Nanqiao/Tingwei	0	497
	Jinmei #5~6	100	20			
	Shangcao #2	900	183			
	Wujing #8~9, #11~12	200	41			
	Caore #12,22	50	10			
	Caore #11,21	200	41			
Way 3	Jinmei #2~4	50	10	Guoliantang/ Huliantang/Sijing/Xinyu/ Nanqiao/Tingwei	840/240/600/360/180/240	526
	Jinmei #5~6	100	20			
	Shangcao #2	900	183			
	Wujing #8~9,#11~12	200	41			
	Caore #12,22	50	10			
	Caore #11,21	200	41			

5. Conclusion

This paper is based on the operation data after Huainan - Nanjing - Shanghai UHV AC put into operation, and calculate the reactive power compensation node and the generator node with high voltage sensitivity of the target node in the network by the sensitivity analysis method. The paper also calculates voltage regulation capability range of UHV access point in Shanghai power grid by the combination of simulation. Its value is 491~526kV, which meets the requirement of system voltage security and stability.

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