Transient Voltage Stability of UHV DC/AC Hybrid Power Grids with Spinning Reserve

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Abstract. This paper studies the mechanism of spinning reserve on transient voltage stability in ultra-high voltage (UHV) DC/AC hybrid power grids. Taking an actual received power grid with an UHVDC system as an example, the transient voltage stability is introduced and a certain scale of spinning reserve has to be retained to keep the transient voltage stability of the system. And then, the steady state of synchronous generators with different spinning reserve is studied using the method of phasor diagram analysis. At last, the relation of spinning reserve, excitation voltage, and dynamic reactive power is analyzed and the mechanism of spinning reserve on transient voltage stability is revealed. The actual received power grid is used to demonstrate the validity of the mechanism.

1 Introduction

For full use of the large-scale renewable energy in the west of China, the ultra-high voltage direct current (UHVDC) transmission system is widely constructed [1]. It is known that the transmission capacity of UHVDC system is large, but the inverter side needs much dynamic reactive power from received AC power grids during the system transient period. For example, under a permanent three-phase short circuit fault near the inverter side of UHVDC system, commutation failure would occur and the maximal reactive power of the inverter side is about one time more than its initial value. Therefore, transient voltage stability is a major concern for UHV DC/AC hybrid power grids, especially for received power grids [2]-[3].

To maintain the transient voltage stability of received power grids with an UHVDC system, on the one hand, dynamic reactive power compensations can be adopted [4]-[5]. At present, static synchronous compensators (STATCOMs) and synchronous condensers (SC) are mostly used to support dynamic reactive power in received power grids [6]-[7]. In [8], a power system with high concentration of induction motor loads applies the dynamic VAR injection to keep short term voltage stability. In [9], synchronous condenser, SVC and STATCOM are compared to show that synchronous condenser is more useful for transient reactive power support and voltage stability.

On the other hand, spinning reserve of synchronous generators (SG) is retained to enhance the dynamic reactive power output. It helps to improve the transient voltage stability of received power grids with UHVDC systems. However, if the spinning reserve of

synchronous generators is great, the power supply capacity would decrease and the cost is too high. Thus, the mechanism of spinning reserve on transient voltage stability in ultra-high voltage (UHV) DC/AC hybrid power grids has become an essential issue that needs to be addressed.

This paper is focused on the mechanism of spinning reserve on transient voltage stability in received power grids with UHVDC systems. Taking an actual received power grid with an UHVDC system in the centre of China as an example, a certain scale of spinning reserve are needed to keep the transient voltage stability. In order to study the mechanism of spinning reserve on transient voltage stability, the steady state of synchronous generators with different spinning reserve is illustrated using the method of phasor diagram analysis in this paper. And then, the relation of spinning reserve, excitation voltage, and dynamic reactive power is analyzed to reveal the mechanism of spinning reserve on transient voltage stability.

Figure 1. Structure of an actual received power grid

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Figure 2. Reactive power of the UHVDC system

Figure 3. Extinction angle of the UHVDC system

Figure 4. Reactive power of loads with induction motor

The remaining of this paper is organized as follows. Section 2 presents the transient voltage stability problem of the actual received power grid with an UHVAC system. In Section 3, the influence of spinning reserve on system transient voltage stability is estimated. The mechanism of spinning reserve on transient voltage stability in received power grids is studied in Section 4. The conclusions are given in Section 5.

2 The transient voltage stability problem of UHV DC/AC hybrid power grids

The steady-state model of the UHVDC system in received power grid can be expressed by the following equations [10].

$$V_{d2} = \frac{3\sqrt{2}}{\pi} k V_{ac} \cos \gamma - \frac{3}{\pi} X_C I_d \quad (1)$$

$$\cos \varphi = \cos \gamma - \frac{X_C I_d}{\sqrt{2} k V_{ac}} \quad (2)$$

$$\begin{cases} P_d = V_{d2} I_d \\ Q_d = P_d \tan \varphi \end{cases} \quad (3)$$

where V_{d2} is the DC voltage of the received UHVDC system. P_d and Q_d are the AC active and reactive power of the received UHVDC system, respectively. φ and γ are the power factor of system and extinction angle, respectively. I_d is the DC current. V_{ac} is the AC voltage of the received UHVDC system. X_C and k are the leakage reactance and ratio of a converter transformer, respectively.

According to equations (1)–(3), we can get that the reactive power of the UHVDC system in received side is added with the increase of DC current. Once commutation failure occurs for the short-circuit ground faults, the received side of UHVDC system needs great reactive power to recover to the normal state. An actual received power grid with an UHVDC system in the centre of China is taken as an example to illustrate the transient voltage stability problem. The simple structure of the actual received power grid is shown in Figure 1. This grid includes a ± 800 kV UHVDC system with the rated capacity of 8000MW. The load center has 9 thermal power generators with the rated capacity of about 4200MW. And the maximal loads reach about 12000MW.

When a permanent three-phase short circuit fault occurs at the line GH, and then the fault line is tripped after about 0.1s. The reactive power and extinction angle of the UHVDC system are plotted in Figure 2 and 3, respectively. It can be seen that the initial reactive power of the UHVDC system is about 1770Mvar with the active power of 4000MW. When the short-circuit fault appears and then be cleared after 0.1s, one time of commutation failure occurs. During the system recovery, the received side of UHVDC system needs more reactive power and the maximal reactive power reaches 2775Mvar fast which is more than about 1000Mvar of its initial value. On the other hand, the reactive power of load with induction motor is plotted in Figure 4. It is shown that the maximal reactive power is about 3 times of its initial value, as illustrated in Figure 4.

Therefore, the voltage stability problem is mainly related to the dynamic reactive power variations of the UHVDC system and loads for the demand side. Transient voltage instability of the actual grid would occur for insufficient supply of dynamic reactive power.

3 Transient voltage stability with spinning reserve

For meeting the dynamic reactive power demand of the UHVDC system and loads, two practical schemes are applied. One is 15 thermal power generators near the load center are applied to provide dynamic reactive power. It indicated that 24 thermal power generators, including 9 thermal power generators in the load center, can support the dynamic reactive power and voltage stability. The other one is a certain scale of spinning reserve of the synchronous generators in the grid is retained to keep the transient voltage stability. It is an

inevitable and yet practical way to enhance the output capability of dynamic reactive power for the actual received power grid.

When the transmission power of the UHVDC system is 4000MW, the total spinning reserve of the synchronous generators in the actual grid is about 3000MW. If the spinning reserve is insufficient, the grid voltage would collapse after the line GH with a three-phase short circuit fault is tripped. As seen in Figure 5, the grid voltage can restore to the normal value with sufficient spinning reserve of synchronous generators during the three-phase short circuit fault. However, the voltage cannot recovery without sufficient spinning reserve. The spinning reserve is meaningful for the actual grid to enhance transient voltage stability.

4 The mechanism of spinning reserve on transient voltage stability

4.1 Static state of synchronous generators with spinning reserve

The active and reactive power of a synchronous generator can be described as the following equations.

$$\begin{cases} P_g = \frac{E_0 V_g}{X_d} \sin \delta = V_g I \cos \theta \\ Q_g = \frac{E_0 V_g}{X_d} \cos \delta - \frac{V_g^2}{X_d} = V_g I \sin \theta \end{cases} \quad (4)$$

where P_g and Q_g are the active and reactive power of the synchronous generator, respectively. E_0 , V_g , I , and X_d are the excitation voltage, generator terminal voltage, generator terminal current, and d-axis reactance, respectively. δ and θ are the generator power angle and power factor, respectively.

In large scale power grid, when a synchronous generator under rated active power state decreases the active power to retain a certain scale of spinning reserve, the generator terminal voltage and reactive power change small. They can be treated as constants, and then we get the following equation by using (4).

$$E_0 \cos \delta \approx c_1, \quad I \sin \theta \approx c_2 \quad (5)$$

where c_1 and c_2 are constants.

According to (5), the generator phasor diagram with different spinning reserve is shown in Figure 6. The vectors with black line represent the rated active power state and none spinning reserve are left. The vectors with red line represent the spinning reserve state. It indicated that the power angle is reduced, and then the generator terminal current and excitation voltage are decreased when the generator operates in the state of spinning reserve.

Figure 5. Bus voltages of the actual grid

Figure 6. Phasor diagram of a synchronous generator

Figure 7. Excitation voltage of a synchronous generator

Figure 8. Reactive power of a synchronous generator

4.2 Transient state of synchronous generators with spinning reserve

Furthermore, taking into account the fast voltage dynamics, the excitation voltage model of a synchronous generator is represented by the differential equation, i.e.,

$$T'_{d0} \dot{E}'_q = E_0 - E'_q - (X_d - X'_d) i_d \quad (6)$$

where E'_{qi} is transient EMF in q-axis, X'_{di} is d-axis transient reactance, i_{di} is d-axis current, T'_{d0i} is open-circuit d-axis transient time constant of a generator.

In the below subsection, it known that the static generator excitation voltage would decrease when the generator operates in the state of spinning reserve. According to (6), the maximal reactive power margin is bigger than that of none spinning reserve.

In the actual received power grid in Figure 1, the transient performance of a thermal power generator under different spinning reserve is given in Figure 7 and Figure 8. The black curve represents the rated active power with the value of 300MW. The red line represents 80% of rated active power and the spinning reserve is 20% of rated active power. Comparing to the rated active power state, it is seen that the initial excitation voltage reduce about 9.5% and the maxmial reactive power deviation increases about 11% under the state of spinning reserve. Also, the maximal reactive power under the two states is all limited by the maximal excitation voltage.

Therefore, the spinning reserve of synchronous generators increases the maximal reactive power deviation during system transient period indirectly and hence can improve the transient voltage stability.

5 Conclusions

The mechanism of spinning reserve on transient voltage stability in UHV DC/AC hybrid power grids is studied in this paper. Taking an actual received power grid with an UHVDC system in the centre of China as an example, a certain scale of spinning reserve is needed to keep the transient voltage stability. The steady state change of synchronous generators with different spinning reserve is given using the method of phasor diagram analysis. And then, the relation of spinning reserve, excitation voltage, and dynamic reactive power deviation is analyzed to reveal the mechanism of spinning reserve on transient voltage stability. The simulation results on an the actual power grid illustrate that: i) the spinning reserve of synchronous generators increases the maximal reactive power deviation during system transient period indirectly and helps to improve the transient voltage stability; ii) the maximal reactive power with different spinning reserve is all limited by the maximal excitation voltage.

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