A new site selection method applied to Synchronous condenser's suppressing transient over-voltage at the sending end of new energy resources

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Abstract. The transient over-voltage will occur in the wind farm near the DC system after commutation failure. In order to reduce the transient over-voltage of wind power plant after the accident of off-grid, improve the stability of the system. This paper mainly studies the placement of the Synchronous condenser in the wind power station. Firstly, the advantages of the Synchronous condenser are analyzed theoretically, and the operation characteristics of the Synchronous condenser under the fault of the DC system are analyzed in detail. Secondly, based on the transient over-voltage area method, a transient over-voltage degree index is proposed, and this index is used as the optimal placement method. Finally, the proposed transient over-voltage index was verified in the PSD-BPA model. The results show that the index is correct and effective in determining the placement point of the Synchronous condenser in the new energy supply.

1. Introduction
In recent years, China’s wind power generation system has developed rapidly, and it has become the largest new energy power generation mode. However, wind energy resources are far from the load center, so it is necessary for HVDC transmission to transfer the electric energy to the remote load center. New energy sources are gathering in the vicinity of DC system on a large scale. The interaction between them and DC operation characteristics is worthy of attention [1].

Generally speaking, DC system operation needs to consume a lot of reactive power while transmitting active power. In the disturbance such as commutation failure and DC blocking, it will not only have a great influence on the converter station of DC, but also cause an over-voltage problem to the nearby power grid [2]. Take wind power as an example, the instantaneous significant rise in voltage may cause the wind turbine to take off the grid due to over-voltage protection action, further resulting in the aggravation of the system voltage, causing a chain reaction. In the actual operation of the power grid, the problem of poor high and low voltage withstand ability of wind turbine is exposed for many times, which is easy to cause the chain off grid fault under the disturbance of the power grid. Therefore, the high voltage chain off grid is the key risk to be prevented in the wind power intensive areas [3-5].

The Synchronous condenser is a synchronous motor specially used for generating reactive power, which can produce different amounts of capacitive or inductive power under or without excitation. When
applied to the power system, it can automatically increase reactive output when the power grid voltage drops and absorb excess reactive power when the power grid voltage rises according to the needs of the system, so as to maintain the voltage and improve the stability of the power system [6]. In view of the problem of transient voltage instability in the transmission end system, a method of optimal configuration of Synchronous condenser with the least control cost is proposed in the literature [7]. Literature [8] proposed a method of reducing DC commutation failure by using Synchronous condenser is proposed. The compensation station is determined by region-line-station and the conclusion is verified by simulation. In order to maximize the dynamic reactive power support performance of the Synchronous condenser, maintain the system stability and reduce the risk of new energy transmission, a new technical scheme is needed to determine the distribution of reactive power compensation of the condenser at the sending end of new energy [9].

2. Introduction of Synchronous condenser

2.1. The advantage of Synchronous condenser in reactive power compensation

The Synchronous condenser is mainly composed of seven parts: the body, the excitation system, the boost transformer, the startup system, the cooling system, the oil system and the control and protection system [10]. It has the advantages of fast tracking speed (can inhibit flicker or impact), wide compensation range (both capacitive and inductive), no influence of harmonic characteristics and low failure rate. The Synchronous condenser can provide fast reactive power output, improve the short-circuit capacity and short-circuit current of the AC power grid, enhance the effective short-circuit ratio of the power grid, reduce the transient over-voltage of the DC transmission end system, and improve the stability of the system. Therefore, Synchronous condenser is the first choice of dynamic reactive power compensation device to enhance the dynamic voltage support ability and improve the stability of AC power grid.

2.2. Reactive power output characteristics of Synchronous condenser under commutation failure

![Figure 1. Characteristic curve of reactive power output of Synchronous condenser](image_url)

In view of the transient overvoltage phenomenon at the DC sending end after the DC system fault, the Synchronous condenser can play the sub transient, transient and steady-state characteristics respectively, and continuously provide dynamic reactive power for the system. Take the reactive power output characteristics of Synchronous condenser under DC fault as an example, as shown in Figure 1:
when commutation failure occurs in the system, the voltage drops. The Synchronous condenser enters the strong excitation state under the sub transient characteristics, which provides emergency reactive power and voltage support for the system and prevents voltage collapse. Under the transient characteristics, it can absorb a large amount of reactive power instantly, restrain the transient overvoltage of converter bus, and reduce the possibility of transient voltage rise transferring to the near area new energy area. Under the steady-state characteristics, the deep input capability can be used to absorb the excess reactive power of the system after commutation failure, suppress the steady-state overvoltage of the DC output system, and improve the level of the steady-state voltage system.

3. Site selection of Synchronous condenser under commutation failure

3.1. Off grid principle of wind turbine transient overvoltage

After commutation failure of DC transmission line, the output voltage of new energy will decrease first and then increase. Figure 2 shows the voltage characteristic curve and reactive power curve of a wind farm under the condition of commutation failure. During the voltage drop stage under the condition of the DC commutation failure, the transient voltage drop will also be transmitted to the nearby wind farm, causing part of the wind turbine to enter the low voltage ride through link, and the active power output will drop, some wind turbine that do not have the ability of low-voltage ride through may be taken off the grid directly. This results in a certain amount of reactive power surplus in the wind farm, which in turn leads to a transient voltage rise in the wind farm station [11].

In the voltage rise stage during the DC commutation failure, the large amount of reactive power surplus of the converter station filter will also cause the transient voltage rise in the near region of the DC system to be transmitted to the near region wind farm, it is superimposed with the effect of voltage rise caused by the reactive power from wind farms. This will cause a more serious over-voltage phenomenon on the wind turbine, resulting in high voltage off the grid consequences.

![Figure 2. Voltage and reactive power curve of a wind farm under commutation failure](image)

3.2. The optimal dynamic reactive power compensation location selection method of new energy delivery terminal

When the dynamic reactive power compensation is applied to the power system, the reactive power/voltage support effect of the same specification of reactive power compensation equipment is different for different compensation stations. The actual over-voltage withstand level of the wind farm shall be in accordance with the standard "when the voltage of the wind farm parallel point exceeds 110% of the nominal voltage, the operation state of the wind farm shall be determined by the performance of the wind turbine unit" in GB/t19963-2011 "technical regulations for wind farm access to power system".
In order to measure the overvoltage degree of different wind farm stations, the concept of relative transient voltage recovery area index is proposed. The influence of the fault on the transient voltage of wind farm station is expressed by the voltage fluctuation degree of new energy in the DC near area in case of commutation failure of DC system. The index is defined as:

\[ u_{j,\text{max}} > 1.1 u_{j,\text{ref}} \quad I = \sum_{j=1}^{M} \left( t_{\text{end}} - t_{\text{start}} \right) \left( u_{j,\text{max}} - 1.1 u_{j,0} \right) \]

(1)

\[ u_{j,\text{max}} \leq 1.1 u_{j,\text{ref}} \quad I = 0 \]

(2)

TVRI is the over-voltage index of a wind farm station under fault; \( j \) is a single station with a voltage level greater than 35kV in the wind farm station (configuration at a lower voltage level will result in too many Synchronous condenser, poor economy, inconvenient unified management, and failure to properly suppress the over-voltage of the converter bus); \( M \) is the total number of stations with voltage level greater than 35kV in the wind farm station; \( t_{\text{start}} \) is the rated time when the voltage of station \( j \) is increased to 110% for the first time; \( t_{\text{end}} \) is the moment when the voltage of station \( j \) drops below the 110% rating and then returns to the 110% rating again and remains below it thereafter; \( u_{j,0} \) is the voltage at the point \( j \) when the system is in stable operation before the failure; \( u_{j,\text{max}} \) is the maximum instantaneous over-voltage of station \( j \) under failure; \( u_{j,\text{ref}} \) is the voltage rating of station \( j \).

TVRI indicates that when the voltage of the affected station is higher than the withstand voltage standard of the wind farm, the product of the over-voltage duration and the voltage rise depth (the drop area of transient voltage). The larger index value is, the greater impact of the fault on the station is. The best dynamic reactive power compensation station can be determined by solving the over-voltage range index value of each of the above stations and sorting according to the value location.

![Figure 3. Selection process of optimal dynamic reactive power compensation location](image-url)
The existing research methods mostly use the optimization algorithm to determine the reactive power compensation area of the weak power grid, it is difficult to analyze the system from the part of power grid parameters. The method proposed in this paper starts with the voltage parameters, it can be clearly analyze the degree of over-voltage of the wind turbine, determine the location of reactive power compensation and provides a reference for the stable operation of the power grid.

When the system disturbance or serious failure, a Synchronous condenser reactive power support effect is not good, according to the TVRI index value can once again select the station to install the appropriate capacity of the Synchronous condenser to achieve the best effect. The flow of this method is shown in Figure 3 below.

4. The simulation verification

4.1. TVRI determines the best reactive power compensation station
In the PSD-BPA power system simulation program, the wind farm near QS DC system and its rectifying side was used as the model. The wiring near the DC system is shown in Figure 4.

![Figure 4. Geographic wiring diagram of QS DC system](image)

The DC transmission system adopts the bipolar ±800kV HVDC transmission line, with the positive and negative electrodes sending out 4000MW and 8000MW respectively. The wind turbine model is the standard type of GE wind motor DFAG_GE_1.5, which is carried out with constant power factor control, and its power factor is 1. The main parameters of the Synchronous condenser are shown in table 1 below:

| Parameters                              | Set value |
|-----------------------------------------|-----------|
| Motor rated capacity                    | 300MVA    |
| direct-axis subtransient reactance      | 0.111pu   |
| direct-axis transient reactance         | 0.165pu   |
| direct-axis subtransient time constant  | 0.05s     |
| direct-axis transient time constant     | 7.46s     |

For the QS DC line, a bus three-phase short circuit fault was set up, and the scene of commutation failure of the DC system was simulated after the fault. The transient over-voltage test of the wind turbine under the DC fault was carried out. The test points were covered in seven different wind farms near the
QS DC system. During the failure of DC commutation, a large amount of reactive power of the ac filter is released, and the bus voltage of the converter station A is greatly increased. As shown in Figure 5(a) and (b), the transient voltage of the converter station A is increased by 0.177pu (141.4kv). At the same time, the transient over-voltage phenomenon of the wind turbine near the DC system is obvious, among them, the transient voltage rise of wind farm g is the largest. The terminal voltage of wind farm g before the disturbance is 0.99pu. After the disturbance, the terminal voltage reaches up to 1.19235, and the transient over-voltage of the fan is up to 1.203 times.

![Voltage curve of converter station A bus](image1)

![Wind farm g voltage response curve](image2)

**Figure 5.** System voltage after DC commutation failure

The transient voltage and voltage elevations of other wind farms near the DC system feeding end are shown in table 2.

| The station of Wind farm | the initial voltage /kV | the highest voltage /kV | the increase of voltage /kV | per unit of voltage increase /pu |
|--------------------------|-------------------------|-------------------------|-----------------------------|--------------------------------|
| a                        | 362.343                 | 422.666                 | 60.323                      | 0.166480                       |
| b                        | 361.969                 | 422.227                 | 60.258                      | 0.166473                       |
| c                        | 361.537                 | 421.726                 | 60.189                      | 0.166481                       |
| d                        | 362.782                 | 423.178                 | 60.396                      | 0.166480                       |
| e                        | 359.846                 | 422.198                 | 62.352                      | 0.173274                       |
| f                        | 357.138                 | 420.481                 | 63.343                      | 0.177360                       |
| g                        | 360.357                 | 424.920                 | 64.563                      | 0.179164                       |

The simulation results of transient over-voltage in the wind farm near the QS DC feeder show that the system’s internal power may fluctuate greatly after the failure of QS DC commutation, and the transient over-voltage of the wind turbine near the converter station is obvious. In accordance with GB/T 19963-2011 technical regulations on wind farm access to power system, "when the grid voltage of wind farm connection exceeds 110% of the nominal voltage, the operation state of the wind farm is determined by the performance of the wind turbine". The maximum value of transient voltage rise in some power stations has exceeded or approached the set value of unit over-voltage protection, so it is urgent to equip with reactive power compensation device to reduce the risk of high voltage off grid.

According to the voltage parameters collected under steady state and transient state, the over-voltage degree index values of each station under fault were calculated, and the calculated results are shown in...
Figure 6. The results show that: among the seven wind farm stations, the transient over-voltage index of e, f and g is large, and the index value of f is the largest. When considering a Synchronous condenser, station f should be the preferred compensation location.

![Figure 6. Transient over-voltage index values of each station in the wind power plant near the DC system](image)

4.2. Verification of site selection method for Synchronous condenser on TVRI

In order to verify the correctness of the above indicators and distribution points, dynamic reactive power compensation is carried out for the three wind farms that are given priority to be equipped with Synchronous condensers. The transient over-voltage peak of wind farms at all stations under failure is recorded as $U_{\text{max}}$, and the peak voltage peak of wind farms after the configuration of Synchronous condensers is recorded as $U_{\text{sc}}$. The difference between $U_{\text{max}}$ and $U_{\text{sc}}$ under different voltage levels in the wind farm is calculated, and the difference value between different voltage levels $U'$ is summed as the index value of the station, the formula is as follows:

$$U' = \sum_{i=1}^{n} (U_{\text{max}} - U_{\text{sc}})$$  \hspace{1cm} (3)

$i$ is a single wind farm station, $n$ is all wind farm stations in this area, $U_{\text{max}}$ and $U_{\text{sc}}$ are defined above.

The higher the value of $U'$, the better the effect of the Synchronous condenser can be proved. The values obtained are shown in table 3, as can be seen from Figure 7 and table 4: After the Synchronous condenser is install, the peak voltage of the wind farm station falls down, which indicates that the Synchronous condenser is indeed weaken the transient over-voltage of the system, and when Synchronous condenser configuration in wind farms f, the maximum voltage difference before and after connection is the largest, the station transient over-voltage suppression effect is most obvious, is better than that of Synchronous condenser configuration on other station, also with TVRI indicators calculated results are consistent, therefore the f station should serve as the best compensation location. When the Synchronous condenser is configured in f wind farm, the subtraction between the voltage peak $U_{\text{max}}$ and the over-voltage peak $U_{\text{sc}}$ in the wind farm under the fault condition is the largest, and the suppression effect on the station transient over-voltage is the most obvious, which is better than the configuration of the Synchronous condenser at other stations. It is also the same with the result calculated by TVRI index, so the f station should be regarded as the best compensation site.
Figure 7. Wind farm f’s voltage

Table 3. $U'$ values of the three stations

| Wind farm station | $U'$ |
|-------------------|------|
| Station e         | 0.335|
| Station f         | 0.449|
| Station g         | 0.349|

Figure 8. Reactive power output of Synchronous condenser after DC commutation failure

After a 300MVA Synchronous condenser is installed in station f, as shown in Figure 8, the Synchronous condenser will generate a large number of inductive reactive power, so as to effectively reduce the surplus reactive power of the wind turbine side under low voltage ride through; under the condition of high voltage ride through, the Synchronous condenser will absorb the redundant reactive power from the filter of DC system (Figure 9). As shown in Figure 10, the transient voltage rise of converter station A is 0.172pu (137.6kv), which is 3.8kv lower than the scheme without Synchronous condenser. Meanwhile, the maximum transient voltage rise of near area A wind farm is reduced to
0.18pu. Before the Synchronous condenser is not equipped, 19 nodes in the wind farm above 35kV will have more serious transient over-voltage phenomenon. However, after the Synchronous condenser is equipped in the wind farm, it will be reduced to 14 nodes. Therefore, the appropriate Synchronous condenser can reduce the system operation control pressure and the risk of high voltage off grid of wind turbine.

![Figure 9. Reactive power output of wind turbine](image)

**Figure 9.** Reactive power output of wind turbine

![Figure 10. System voltage after DC commutation failure with Synchronous condenser](image)

(a) Bus voltage of a converter station  
(b) Wind farm voltage

**Figure 10.** System voltage after DC commutation failure with Synchronous condenser

5. **Conclusion**

To sum up, this paper proposes a method for selecting the optimal dynamic reactive power compensation location of the Synchronous condenser in the new energy side of the near DC segment. Firstly, the transient over-voltage of new energy in the DC near region after commutation failure is studied. Based on the area method, the measurement index of the degree of transient over-voltage is proposed. The optimal distribution scheme of reactive power compensation of the Synchronous condenser is obtained by calculating the voltage parameters of the power grid system under transient and steady state conditions. Assembling the Synchronous condenser for reactive power compensation to reduce the risk
of off-grid under transient over-voltage; Finally, the simulation results show that the proposed method is correct. The index proposed in this paper can quickly determine the location of reactive power compensation and provide support for the safe and stable operation of the new energy supply system.

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