Calculation Method of DC Limit Power Considering Influence of New-generation Synchronous Condensers

Zuowei Wang, Fan Xiao*
1Hubei Electric Power Research Institute, SGCC, Wuhan, China

Corresponding author: xiao103fan@163.com

Abstract. Because the new-generation synchronous condenser has strong excitation ability and leading power factor operation ability, the DC transmission power value will be effectively improved. In this paper, the reactive power limit value models of the new-generation synchronous condensers under phase-in and phase-lag operation conditions were established. Then, the correlation model between AC and DC systems considering the effects of new-generation synchronous condensers is established. Based on this, the commutation angle of DC and the parameters related to the inverter side are calculated under rated conditions. Moreover, the AC system equations is combined to solve the potential of the equivalent AC system and the power angle of DC bus voltage. Then, using DC current as an independent variable to find the maximum DC power considering the reactive power limit value of the new-generation synchronous condensers. Therefore, the initial reactive power output of new-generation synchronous condensers and the maximum power of DC transmission can be calculated. The results of this paper provide a theoretical basis for improving DC transmission power in power system analysis, and have an important role in promoting the consumption of renewable energy at the DC-fed AC grid.

Keywords—HVDC, new-generation synchronous condenser, maximum power of DC, Calculation Method

1 Introduction
With the increasingly serious energy shortage and environmental pollution, accelerating the development and utilization of renewable energy has become an important problem to be solved in the energy field of China. However, due to the influence of energy resource endowment, the load center and renewable energy base in China have the characteristics of long-distance reverse distribution, so it is necessary to adopt long-distance large-capacity transmission potential. Due to the outstanding advantages of UHVDC transmission project in technology, economy and security, China has become the country with the most extensive application prospect of long-distance DC transmission in the world. However, the conventional DC converter station needs to consume a lot of reactive power, which is mainly provided by static reactive power compensation device in the converter station. When the system has large disturbance, the reactive power absorbed by the converter station of the DC system may increase significantly, and the output of the static var compensation device will decrease, which will lead to the shortage of local dynamic reactive power compensation ability and the risk of grid voltage instability increase in amplitude. Compared with the static var compensation device, the new-generation synchronous condenser (NGSC) has large reactive power compensation capacity. At the same time, when the grid voltage drops, the excitation system of NGSC can automatically adjust
and implement forced excitation, and continuously provide reactive power to the system. Therefore, with the increasingly prominent problem of "strong direct and weak AC" in the power grid, accelerating the deployment process of new-generation synchronous condensers in the UHV power grid, improving the voltage stability and dynamic reactive power support capacity of the power grid, is of great significance to the safe and stable operation of the AC / DC grid. Since the maximum DC power is related to the AC power grid and other factors, the access of multiple new-generation synchronous condensers may affect the maximum DC operating power. Therefore, it is necessary to study the influence of the condenser on the maximum DC power. However, there are few studies on this topic at home and abroad. In [1], the relevant parameters of the new-generation synchronous condensers are considered. In [2], the sub-transient process, transient process and steady-state process of the new-generation synchronous condensers are considered under fault conditions. In [3], the application of new generation synchronous condenser and power electronic reactive power compensation device, such as STATCOM and SVC, etc., in AC / DC power grid are compared. In [4], the influence of new-generation synchronous condensers is analyzed in AC / DC power grid. In [5], the influence of 300 Mvar new-generation synchronous condensers on the stability of Hunan power grid is studied. However, the above research did not consider the impact of the new-generation synchronous condensers on the maximum DC transmission power after it is connected to the power grid. In [6], the configuration of the new-generation synchronous condensers connected to the UHV converter station was studied, but the effect of the new-generation synchronous condenser on the UHVDC transmission power was not studied. Therefore, the influence of the new-generation synchronous condensers on the maximum DC transmission power after being connected to the DC converter station needs to be studied. Based on this, the correlation model between AC and DC systems was established. Then, the reactive power limit model of the new-generation synchronous condensers in the phase-in and phase-lag operation is established. Based on this, according to the new-generation synchronous condensers reactive power limit model and the transmission and receiving end grid converter station models, the maximum DC transmission power is solved.

2 Operating characteristic equation of DC inverter station
Taking the DC system with two new-generation synchronous condensers in the converter station shown in Fig. 1 as an example, the influence of short circuit ratio of feeding AC system on voltage stability of converter buses is analyzed.

![Fig.1. Structure of DC system with NGSCs](image)

In the figure 1, \(\gamma/\mu\) is the turn-off angle and commutation angle of the commutation valve, \(U_{\text{pcc}}/\delta_0\) is the commutation bus voltage, \(U_d\) and \(I_d\) are the DC voltage and DC current, \(P_d\) and \(Q_d\) are the active power and reactive power transmitted by the DC system, \(P_{ac}\) is active power of the AC system and \(Q_{ac}\) is reactive power generated by reactive power compensation device; \(X_c\) is commutation reactance; \(Z/\angle \theta\) is equivalent impedance of AC system;
$E \angle \delta_e$ is equivalent potential of AC system. Ignoring the DC harmonic component and the active power loss of inverters, converter transformers and reactive power compensation devices, the system characteristics can be described by equation (1).

$$
\begin{align*}
P_d &= C U^2 (\cos 2\alpha - \cos (2\alpha + 2\mu)) \\
Q_d &= C U^2 (2\mu + \sin 2\alpha - \sin (2\alpha + 2\mu)) \\
I_d &= K U (\cos \alpha - \cos (\alpha + \mu)) \\
U_d &= \frac{P_d}{I_d} \\
P_{ac} &= EU \cos (\delta + \theta) - U^2 \cos \theta \left| Z \right| \\
Q_{ac} &= EU \sin (\delta + \theta) - U^2 \sin \theta \left| Z \right| \\
Q_c &= B_c U^2 + \Delta Q_{SC} \\
P_d - P_{ac} &= 0 \\
Q_d - Q_{ac} - Q_c &= 0 \\
I_d &= \frac{a U \cos \alpha - b U \cos \gamma}{X_d}
\end{align*}
$$

(1)

Where, $\tau$ is the tap gear of converter transformer.

The adjust reactive power increase $\Delta Q_{ac}$ can be expressed as:

$$
\Delta Q_{ac} = Q_{cx_{SC}\text{max}} - Q_{inv_{SC}0}
$$

(2)

Where, $Q_{cx_{SC}\text{max}}$ is the limit of the reactive power of the new-generation synchronous condensers under the lagging operating conditions and $Q_{inv_{SC}0}$ is the limit of the reactive power of the new-generation synchronous condensers under in-phase conditions.

### 3 Reactive power characteristics of New-generation Synchronous Condensers

The excitation model of the new-generation synchronous condensers includes the closed-loop control of terminal voltage of the new-generation synchronous condensers, the closed-loop control of excitation current, the control of constant reactive power regulation, and the combined control model of reactive power and system voltage.

![Fig.2. Typical Structure of Voltage Ring Control Model for new-generation synchronous condenser](image)

According to the Parker equation of the unit, a transient electromagnetic equation for a new-generation synchronous condenser is established. At the same time, according to the structure of the NGSC excitation control system, the reactive power output equation of a NGSC can be obtained.
Where, \( U_{\text{rel}} \) is stator voltage after the occurrence of grid voltage dip. \( E_{0m} \) is stator excitation electromotive force. \( T_d \) and \( T_{d'} \) are transient time constant and subtransient time constant of d axis, respectively. \( X_d \) and \( X_{d'} \) are transient reactance and sub transient reactance of d axis, respectively. \( x_{\text{ad}} \) is excitation inductance in d axis. \( x_{\text{de}} \) is equivalent leakage reactance, \( x_{\text{de}} = x_d + x_v \). \( x_d \) is reactance in d axis, \( x_v \) is external reactance between the generator and the short-circuit point. \( U_{\text{rel}} \) is initial excitation voltage. \( R_{\text{rel}} \) is excitation winding resistance. \( U_{\text{m}} \) is excitation voltage in steady state after fault. \( T_{sk} \) is time constant of NGSC in transient process, which can be expressed as \( T_{sk} = T_d R_{m} / (R_{m} + R_d - x_{\text{ad}} x_{v} K_{S} \cos \alpha / x_{\text{de}}) \).

Because of the low excitation and strong excitation functions of the new-generation synchronous condensers, the reactive power output can be obtained according to the requirements of low excitation and strong excitation under extreme conditions. According to the relevant regulations, the new-generation synchronous condensers can operate without excitation voltage under low excitation conditions, and the excitation voltage needs to be 3.5 times of the rated excitation voltage under strong excitation conditions. The phase advance and hysteresis limits of a new-generation synchronous condenser can be obtained. Thus, the maximum reactive power of a new-generation synchronous condensers under lag-phase operation and in-phase conditions can be expressed:

\[
Q_{\text{cc,SC max}} = \begin{cases} 
U^2 / X_d \approx K_c S_N, & U > E_0 \\
(k_{jm} - 1) U^2 / X_d \approx (k_{jm} - 1) K_c S_N, & U < E_0
\end{cases}
\]

Where \( Q_{\text{cc,SC max}} \) is maximum reactive power of a new-generation synchronous condenser. \( S_N \) is rated capacity of a new-generation synchronous condenser. \( X_d \) is synchronous reactance of the new-generation synchronous condenser in the straight axis. \( X_q \) is synchronous reactance of a new-generation synchronous condenser in quadrature axis. \( K_{SC} \) is short circuit ratio of a new-generation synchronous condenser. \( U \) is the unit voltage. \( k_{jm} \) is maximum excitation multiple of rotor.

4 Commutation angle and correlation parameter

According to formula (1), the commutation angle and inverter-side grid correlation coefficient can be obtained.

\[
\mu = \frac{1}{2} \arccos(\cos 2\alpha - P_d / c U^2) - \alpha
\]

\[
K = \frac{I_d}{U (\cos \alpha - \cos (\alpha + \mu))}
\]

Where \( I_d \) is the DC current and \( U \) is the DC bus voltage.
Due to $K$ is a constant related to the inverter-side system, the value of $K$ can be calculated by equation (5) according to the values of $I_d$, $U$, $\alpha$ and $\mu$ under the rated working conditions, which can be used for subsequent calculations. Based on this, according to the six equations 4, 5, 6, 7, 8, and 9 in equation (1), solve the AC potential and DC bus voltage work angle considering the initial reactive power output of the new-generation synchronous condensers.

$$E = \frac{C|Z|U(\cos 2\alpha - \cos(2\alpha + 2\mu))}{\cos(\delta + \theta) - U \cos \theta}$$

$$CU^2(\cos 2\alpha - \cos(2\alpha + 2\mu)) \sin(\delta + \theta) - U^2 \frac{\sin \theta}{|Z|}$$

$$+ B_U^2 + \Delta Q_{sc} = CU^2(2\mu + \sin 2\alpha - \sin(2\alpha + 2\mu))$$

Then, assuming $U = 1$ p.u., each electrical quantity $P, Q, U, P, Q, Q_{sc}$, and $\Delta Q_{sc}$ can be calculated according to $\Delta Q_{sc} = Q_{sc, max} - Q_{av, sc}$, it can be obtained that the initial reactive power value of the new-generation synchronous condenser is adjusted for the DC inverter side. Moreover, the calculated reactive power provided by the new-generation synchronous condenser is within its allowed reactive power range need to be determined. If it is within the range, use the DC current as an independent variable to solve the DC static power limit value. If the initial output of the new-generation synchronous condenser is within a given range, the value of the new-generation synchronous condenser is substituted into the seventh equation in equation (1). The DC current $I_d$ is solved by the $\frac{dP}{dI_d} = 0$ under the DC transmission power reaches the maximum value $P_{dmax}$ condition. Otherwise, the initial reactive power output of the new-generation synchronous condenser is adjust to within its allowable output range, and the maximum DC power can be recalculated.

![Fig.3. Schematic diagram of DC maximum reactive power calculation process considering new-generation synchronous condenser](image-url)
5 Simulation analysis

![Diagram of Converter station with synchronous condenser.]

According to the actual transmission system of UHVAC in Qishao DC project, a AC/DC power grid co-simulation platform with new-generation synchronous condensers was constructed based on the PSCAD simulation software. It is used to analyze the influence of the new-generation synchronous condenser and the maximum DC operating power. Simulation model of new generation synchronous condenser considering magnetic saturation is shown in Fig. 4.

In order to analyze the influence of steady-state initial reactive power of the condenser on its transient reactive power output capability, set the power supply voltage to drop to 0.8un in 30s, and simulate and analyze the transient reactive power output of the condenser under the conditions of initial reactive power of 0p.u., -0.4p.u. and 0.8p.u. the simulation results are shown in Fig.5.

![Graphs showing transient reactive power output under low voltage condition.]
According to the simulation results, the initial reactive power of the steady-state operation of the new-generation synchronous condenser will affect the reactive power output capacity of the new-generation synchronous condenser. With the increase of the initial reactive power of the new-generation synchronous condenser, the reactive power transient reactive power output of the new-generation synchronous condenser increases, and the transient reactive power increment decreases.

**Fig.6.** Schematic diagram of the maximum DC transmission power of the new generation synchronous condenser under different initial reactive power conditions.

Based on the established joint simulation model of DC and new-generation synchronous condenser, the research on the maximum DC transmission power under different initial reactive power output conditions of the new-generation synchronous condenser is carried out. In this paper, the schematic diagram of the maximum DC transmission power is shown in Figure 1 under the conditions of initial reactive power of the new-generation synchronous condenser is -50Mvar, 0Mvar and 50Mvar. It can be seen from the Fig.6 that under the condition of transmitting different DC current values, the maximum transmission power value of DC is related to the initial reactive power output of the new generation synchronous condenser. The simulation diagram verifies the validity of the proposed calculation of the maximum DC power. It plays an important guiding role in the system analysis and calculation of the new-generation synchronous condenser after AC-DC power grid.

6 Conclusion

In order to improve the dynamic reactive power support capability and DC operation level of the power grid, many new generation synchronous condenser is connected to the power grid. Therefore, the maximum DC transmission power is significantly affected. In this paper, the correlation model between AC and DC systems was established. Then, the reactive power limit model of the new-generation synchronous condensers in the phase-in and phase-lag operation is established. Based on this, according to the new-generation synchronous condensers reactive power limit model and the transmission and receiving end grid converter station models, the maximum DC transmission power is solved. The research results of this paper have important guiding role for the system analysis and calculation after the new-generation synchronous condenser of AC / DC power grid.

References

[1] Li Zhiqiang, Jiang Weiyong, Wang Yanbin, et al. Key technical parameters and optimal design of new types of large capacity synchronous condenser[J]. Large Electric machine and Hydraulic Turbine, 2017(4): 15-22.

[2] Wang Yating, Zhang Yichi, Zhou Qinyong, et al. Study on application of new generation large capacity synchronous condenser in power grid[J]. Power System Technology, 2017, 41(1):22-28(in Chinese).

[3] Jin Yiding, Yu Zhao, Li Mingjie, et al. Comparison of new synchronous condenser and power electronics reactive-power compansation devices in applications of UHV DC/AC grid[J]. Power System Technology, 2018, 42(7):2096-2103(in Chinese).
[4] Zhang Kaiyu, Cui Yong, Zhuang Kanqin, et al. Analysis of the influence of synchronous condensers on receiving-end grid with multi-infeed HVDC[J]. Power System Protection and Control, 2017, 45(22): 139-143 (in Chinese).

[5] Cui Ting, Shen Yangwu, Zhang Bin, et al. Influences of 300 Mvar synchronous condensers on the stabilities of Hunan power grid [J]. Hunan Electric Power, 2016, 36(3): 1-3, 8 (in Chinese).

[6] Li Desheng, Luo Jianbo. Typical design of security and stability control system for UHVDC transmission[J]. Automation of Electric Power Systems, 2016, 40(14): 151-157 (in Chinese).