New research progress of large capacity new synchronous condenser

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Abstract. With the increase of HVDC (high voltage direct current) transmission system, the new large-capacity synchronous condenser is the most suitable device to meet the dynamic reactive power demand of the power grid system. Therefore, it has gradually become one of the research hot topics. Based on this, the paper systematically summarizes the research status of the new synchronous condenser. Firstly, the operation principle of the synchronous condenser is introduced from four aspects: its reactive power characteristics, operation state and the typical type and control strategy. Secondly, by comparing it with power electronic reactive power compensation equipment, the superior dynamic reactive power output characteristics of the new synchronous condenser are expounded, and the influence factors are analysed, the example that stable grid voltage is given. Finally, the latest development of the state monitoring technology of the synchronous condenser is summarized from both the existing fault diagnosis technology and parameter identification technology. In this paper, the basic theory, control strategy and operation state monitoring of the new synchronous condenser are summarized, which could provide reference for the further research.

1.Introduction
In the last century, the traditional synchronous condenser had been withdrawn from the power grid because of high cost and insufficient capacity. In recent years, with the development of UHVDC (Ultra high voltage direct current) transmission project, the new synchronous condenser is used to meet the transmission demand and become the research hot topic again. Based on the design of traditional synchronous condenser, new synchronous condenser dynamic response ability and reactive
power compensation ability are optimized. Its regulation ability is little affected by the system, it possess stronger voltage ride through ability and excitation characteristic. It could maintain the power system voltage stability and provide short-circuit capacity when the fault happened in system, and own strong support ability to the system transient process [1].

With the rapid development and wide application of UHVDC in China, the large-capacity DC power transmission is required to match the large-capacity dynamic reactive power for the shortage of dynamic reactive power supply at the sending and receiving end because voltage supporting capability is weak. It is an effective scheme to solve the problem of reactive power shortage that large-capacity new synchronous condenser are put into UHVDC and transmission respectively as dynamic reactive power compensators. For the DC receiving end grid, the problem of DC commutation failure and the problem of voltage stability of the power grid are becoming more and more obvious, it could improve the DC multi-terminal feed short circuit ratio, reduce the risk of multiple DC circuit commutation failure in the meantime, and improve the system voltage stability level under serious faults. UHVDC line are mostly built in remote areas where wind and photovoltaic power are widely distributed. The short-circuit capacity is small, and the fault-tolerant capability is poor to DC faults at the sending end, which easily leads to large-area wind turbine tripping faults, the synchronous condenser could increase the system short-circuit ratio, reduce the risk of new energy high-voltage tripping, restrain the over-voltage [2,3].

The large capacity new synchronous condenser is put into operation in the power grid, which mainly solves the reactive power compensation of grid fault, but the impulse current when the power grid fault occurs will have a great influence on the synchronous condenser for a long time, when it is serious, the temperature is too high, the insulation is damaged, the machinery vibrates, causes the fault, thus lead to the power grid fault further to enlarge [4]. Although the synchronous condenser system is equipped with relay protection, it can’t effectively prevent the failure, nor effectively identify the type and location of the failure. Therefore, it is urgent to carry out the research on condition monitoring of the new synchronous condenser in order to ensure its ability to deal with power grid faults.

The paper first introduces the operation principle and function of the new synchronous condenser, and compares it with the traditional synchronous condenser and the power electronic reactive power compensator, the dynamic output reactive power characteristics of the new synchronous condenser. Secondly, it introduces the two main types and the feature of synchronous condenser and the example of stabilizing the sending end voltage in Hami area. The influence of operation condition and state parameters on the output dynamic reactive power characteristics of the new synchronous condenser is analyzed. At last, the monitoring technology of the new synchronous condenser is summarized from the aspects of state monitoring, fault diagnosis and parameter identification.

2. The principle and function of the synchronous condenser

The synchronous condenser is a kind of no-load synchronous generator, which could operate in three states: leading-phase, delayed-phase and no-load operation. When in no-load operation, the synchronous condenser works in the normal excitation state, neither absorb nor emit reactive power. When the it is over-excited, the stator current lags behind the voltage, and the inductive reactive power is sent to the power grid, when the system is under-excited, the stator current is ahead of the voltage, and the inductive reactive power is absorbed from the grid to avoid over voltage.

The HVDC UHV (Ultra high voltage) transmission terminal is prone to happen DC blocking fault, and there is a large amount of reactive power remains in the power grid, which leads to over-voltage and affects the stability of the grid. The synchronous condenser possess superior phase-leading ability to ensure its rapid response to faults and processing capacity [5].

DC UHV converter station usually locates near the load center, the probability of inverter commutation failure is high, which makes the reactive power is insufficient and the voltage is too low. The synchronous condenser possess superior delay capability to provide enough inductive reactive power to the power grid to maintain voltage stability.
3. Reactive power characteristics of new synchronous condenser

With the development of UHVDC, new synchronous condenser is expected to be an important reactive power compensation device in the future due to its large reactive power and strong dynamic response capability [6].

3.1. Performance comparison and coordinated operation between synchronous condenser and power electronic device

3.1.1. The performance comparison between synchronous condenser and the power electronic device

The existing reactive power compensation equipment can’t meet the requirement of UHVDC large-capacity reactive power and dynamic voltage support. To the SVG/STATCOM, short-time overload output capacity is insufficient. The traditional synchronous condenser owns small capacity and slow dynamic response. The capacity of superconducting synchronous condenser is small, the auxiliary system is complex, and the work about operation and maintenance are heavy.

There are essential differences in principle between the new synchronous condenser and power electronic devices such as SVC, SVG, STATCOM, etc [7]. In the dynamic response aspect, all of them have the response ability, and power electronic devices need to be calculated by circuit before it output reactive power response. In the reactive power capacity, SVC device is superior to STATCOM in the delayed-phase capacity, and the synchronous condenser is far superior to power electronic equipment, and durable. The reactive power of power electronic devices is greatly affected by voltage (almost squared relation with the voltage), while the reactive power of synchronous condenser is hardly affected by voltage fluctuation.

Reference [8, 9] compares the dynamic response of SVC to power grid fault with that of synchronous condenser. The results show that SVC has good dynamic response to slight fault, and the reactive power support capability is insufficient to serious fault, the synchronous condenser still provides enough reactive power to stabilize the grid voltage. The performance comparison of several reactive power compensation devices is shown in Table 1.

| Performance             | Capacitor | SVC      | STATCOM | Synchronous condenser |
|-------------------------|-----------|----------|---------|-----------------------|
| Voltage regulation      | negative  | positive | positive| positive              |
| Withstand overvoltage   | none      | none     | better  | good                  |
| High-order harmonic     | none      | none     | less    | less                  |
| Control mode            | Discontinuity | discontinuity | continuity | discontinuity |
| Starting speed          | medium    | quick    | quick   | slow                  |
| Reaction speed          | quick     | quick    | quick   | slow                  |
| Overload bearing        | poor      | poor     | poor    | good                  |
| Regulating accuracy     | poor      | poor     | good    | good                  |

3.1.2. The coordinated operation of synchronous condenser and power electronic device

The new synchronous condenser could generate reactive power continuously and effectively, and bears a high multiple of strong excitation in short time. It is suitable for a long time and serious voltage fault, however, the power electronic device is quick in response, but sensitive to the voltage variable. Therefore, in the actual power grid, two kinds of equipment could play their respective
special characteristics together, coordinate control, and work in different time and degree when the power grid fault occurs, working together to keep the voltage stable.

At present, the power electronic compensation device and the new synchronous condenser have already played the important role of stabilizing voltage together in the power grid. In the paper [8], a coordinated control strategy based on SVC between converter station side regulator and wind farm side to control the wind turbine tripping of high voltage DC sending end wind turbine is proposed, the time-sharing of reactive power response, excitation control and SVC reactive power regulation to suppress the transient voltage drop or rise above the wind turbine tripping protection threshold value.

In recent years, due to frequent and deep voltage ride through, large amount of SVG installed at grid-connected points of new energy field stations that has been damaged and the economic losses is severe. Some scholars have proposed to install small capacity synchronous condenser at grid-connected points to regulate reactive power, to improve the voltage ride through capability of the new energy field station [10].

3.2. Typical structure of new synchronous condenser

According to different operating conditions, engineer has designed and developed the largest (300 MVAR) two typical structures of the new synchronous condenser: air-cooled and water-cooled synchronous condenser in the world. The air-cooled condenser is usually used in water-deficient areas, while the water-cooled condenser is used in water-rich areas. The performance comparison is shown in Table 2.

| Item                  | Double water internal cooling condenser | Air-cooled condenser          |
|-----------------------|-----------------------------------------|--------------------------------|
| Output range          | low temperature rise, slightly stronger overload capacity | high temperature rise, slightly weaker overload capacity |
| Water consumption     | primary cooling water is about 83 tons per hour | none |
| Occupation area       | small                                   | big                           |
| Rotor weight          | 59 tons                                 | 71 tons                       |
| Stator weight         | 185 ton                                 | 273 tons                      |

3.3. An example of improving the stability of sending end power grid by using synchronous condenser

Take the UHVDC transmission sending end as an example: The power grid structure in Hami is complex (Figure 1). In addition to the traditional coal-fired power, large-capacity wind power and photovoltaic power are connected, and the output power fluctuates greatly. The power capacity of Hami to Zhengzhou transmission is 8000MW, the scale of new energy power (wind and photovoltaic power n) is relatively large, and the transient voltage of the near zone of wind turbine may exceed its maximum allowable operating voltage in case of DC commutation failure, causes the wind turbine high pressure to fall off the grid. As an important UHVDC transmission hub, the Tian-shan converter station has installed two new 300 MVAR synchronous condensers.
By experiment and calculation, the voltage stability effect of install the new synchronous condenser or not is shown in Table 3. Because of its fast reactive power regulation ability, the two synchronous condensers could effectively restrain the transient over-voltage, shorten the recovery time and reduce the wind turbine tripping probability. It shows that it is of great significance to install new synchronous condenser as the standby dynamic reactive power equipment in Tian-shan converter station to ensure the safe and stable operation of DC transmission.

Table 3. Variation of bus voltage at Tianshan converter station during three-phase grounding fault of Sandaojing

| Name       | Upper voltage limit/pu | Lower voltage limit/pu | Max fluctuation/pu | Recovery time/s | Output reactive power of condenser/Mvar |
|------------|------------------------|------------------------|--------------------|-----------------|---------------------------------------|
| Before fixed condenser | 1.15 | 0.77 | 0.38 | >10 | 0                                      |
| After fixed condenser   | 0.98 | 0.79 | 0.19 | 7   | 705                                   |

4. Research direction of new synchronous condenser

4.1. Optimization of reactive power characteristic

4.1.1. The optimization of steady-state characteristics
The steady-state characteristics are mainly shown in the relationship between the excitation current and reactive power. The over-excitation multiple (up to 3.5 times over-excitation) is large, which provides strong reactive power for the system. Due to the coupling of electromagnetic field thermal field and mechanical force, the duration of intense excitation is long, and it is difficult to calculate accurately.

4.1.2. Parallel operation of the synchronous condenser
Generally, there are two synchronous condenser installed in the same converter stations at least, the start-up and excitation control of the synchronous condenser, the improvement of reactive power and the determination of control strategy need further study. The leading-phase capacity of the large
capacity synchronous condenser is lower than the delay-phase capacity, which makes the provided
dynamic reactive power reserve and dynamic recovery reactive power reserve to the power grid by the
two synchronous condenser is unbalance, it is necessary to study the coordinated control strategy of
multiple synchronous condenser, balance the dynamic reactive power output and the dynamic reactive
power output of synchronous condenser, deal with different types of grid faults in AC and DC systems
effectively, and reduce the input quantity of filter groups, increase the number of backup filters[11].

4.1.3. Transient performance optimization of synchronous condenser
The optimization of the transient performance of the synchronous condenser mainly lies in the
improvement of the speed of the synchronous condenser response, which requires the generation of
powerful reactive power in the shortest possible time. By simulation calculation: the output reactive
power from 0 to 500 Mvar needs only 0.6 s (Figure 2), less than 1.2 s that state grid requirements.

![Figure 2. Variation of bus voltage at Tianshan converter station during three-phase grounding fault of Sandaoling](image)

By optimizing the structure of stator rotor and air gap, the output reactive power capacity and
rapidity can be increased, ensure the end of winding can’t be deformed, reduce the temperature
volume and cost, in the fact, they are coupled among electromagnetic field thermal field and
mechanical force, so it is very complicated and difficult to carry out three-dimensional analysis and
calculation. In addition to the variety of operating conditions, adopt and improve new materials and
processes cooling methods continuously, there is lots of optimization work to do.

The research results show that the output transient reactive power performance of synchronous
condenser mainly depends on the sub-transient reactance and the short circuit reactance of the main
transformer. However, if the direct-axis reactance is too small, the output reactive power will be
suppressed for a short time. In addition, the open-circuit time constant of the straight axis has a certain
influence on the output transient capability of the synchronous condenser (they are inversely
proportional). The excitation parameters have a great influence on the output reactive power
characteristics of the synchronous condenser. Increase the excitation resistance and decrease the
excitation reactance could reduce the dynamic response time [12].

4.2. Operational monitoring and condition assessment
When the fault occurs in power grid, the synchronous condenser possess good dynamic regulation
ability. The accuracy of the model is directly related to the monitoring level of the dynamic output
capability of the synchronous condenser, so the accurate parameters are the basis of the analysis of the
synchronous condenser operation characteristics.

At present, the parameter identification method is commonly used to estimate the parameters of the
synchronous condenser. The parameter identification method uses monitoring information to identify
the main parameters (such as resistance, reactance, etc.) based on the detected operating parameters of
the synchronous condenser, judging the operating characteristics. The synchronous condenser is a kind
of synchronous generator, but it is different from the traditional synchronous generator in operating
characteristics. Based on the parameter identification method of synchronous generator, the
researchers put forward many improved methods, which are applied to parameter identification of synchronous condenser.

4.3. Fault diagnosis
The research of fault diagnosis about new synchronous condenser is just beginning, and there is little in-depth study on many typical faults. For example, the original data of the actual operating synchronous condenser is very scarce when the fault occurs. At present, the typical fault operation of the synchronous condenser is studied by simulation and some experiments on site. The on-line monitoring of operation parameters (such as voltage, current, torque, etc.) can be done by means of on-line fault diagnosis technology.

(1) Stator inter-turn short circuit is a common fault, which is also one of the most serious faults. If the stator inter-turn short-circuit fault isn’t be found in time and properly handled, it probably will gradually evolve into inter-phase short-circuit, resulting in shut down. Therefore the diagnosis of stator inter-turn short circuit is an essential part of its fault diagnosis.

(2) Rotor turn-to-turn short circuit fault is also a common fault, the slight turn-to-turn short circuit is often ignored. If the faults continue to develop, the rotor current will increase significantly, the winding temperature will increase, the output reactive power will decrease, and other faults will occur, resulting in a larger accident.

(3) Because of the influence of machining and operating environment, the rotor eccentricity will appear in the long-term operation of the synchronous condenser. In the stator and rotor on the uneven electromagnetic pull, resulting in bearing wear and rotor surface cracking. So it is very important to diagnose the rotor eccentricity fault.

(4) When the new synchronous condenser breaks down in the power grid, the strong excitation depth and the duration are different, the electromagnetic field the thermal field and the end winding force are all in the dynamic change, the electric thermal and mechanical coupling analysis is also the research difficulty [13, 14].

5. Conclusion
With the application of new synchronous condenser in UHVDC project, the research on its reactive power characteristics and state monitoring is of great significance. Firstly, the operation principle and structure of the new synchronous condenser are introduced, and the relationship between its operation state and power grid is analyzed. Then the paper summarizes the output reactive power characteristics of the new synchronous condenser, compares it with power electronic compensation device, and analyzes the advantages of the new synchronous condenser. The practical example that stabilize the sending end voltage of Hami area is been proposed. Finally, the state monitoring technology of the new synchronous condenser is analyzed and summarized. This paper summarizes the research status from four aspects of the operation principle, the reactive power characteristic analysis, the state monitoring technology and the capacity and location selection, and provides a reference for further research. At the present stage, the research on the new synchronous condenser is very preliminary, in the future research, there are still lots of work to be done in-depth.

(1) Because the actual operating condition of the synchronous condenser is very complex, the design optimization and modeling analysis are not accurate at the present stage, it is necessary to improve the precision of model and parameter identification, the rationality of structure design and the performance of reactive power compensation.

(2) For large-capacity power system, the coordinated control of SVC, SVG and STATCOM and the reactive power characteristics under various working conditions still need to be studied. The control strategy of excitation system with parallel operation of multiple synchronous condenser still needs to be improved.

(3) The mechanism of condition monitoring and evaluation is not perfect, and the state characteristics of various faults are not clear, which needs further research.
(4) According to the different condition of the structure and capacity of the power grid, the research about the access position and capacity of the synchronous condenser need to be studied.

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