

Research and Application of Protection Principle of 300Mvar Class New Synchronous Condenser

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SUMMARY

In order to solve the problem of energy distribution imbalance in China, HVDC transmission technology has been widely used to realize asynchronous power grid interconnection in different regions. The DC converter station needs to consume a large amount of reactive power, which was mainly provided by static var compensator and static var generator in the converter station. However, when the grid voltage is reduced, the static var compensator and static var generator cannot achieve full reactive power output, but the condenser excitation system can automatically regulate and implement mandatory excitation, and continuously provide reactive power to the system. In addition, the new synchronous condenser not only meets the demand for steady reactive power, but also provides transient dynamic reactive power support, suppresses voltage fluctuations and reduces the probability of commutation failure in HVDC, which is of great significance to improve the voltage stability of the UHV AC and DC hybrid power grid, therefore it has been widely applied in DC converter stations.

By the analysis the operation characteristics of the synchronous condenser, comparison of the differences between the synchronous condenser and the large synchronous generator, the protection solutions of the synchronous condenser are as follows.

1. The synchronous condenser cannot start on its own, and usually started by the Static Frequency Converter (SFC). During the starting process, the maximum stator current is about 20% rated current, and the maximum stator voltage is about 10% rated voltage. The U / F value ranges from 0 to 0.5. When the synchronous condenser is dragged from static to 1.05 times the rated speed, the SFC is disconnected, the voltage is increased to the rated value by the excitation system, and then the synchronous condenser will be synchronously interconnect to the power grid. During the process, all electrical quantities are frequency-variable and includes high harmonic components, so measures to prevent the regular protection maloperation should be taken and also the frequency conversion start-up process protection should be adopted.

2. The synchronous condenser has no prime mover, after connecting to the grid, it absorbs a small amount of active power to maintain the rated speed and simultaneously generates or absorbs reactive power. The rotation speed synchronously changes with the grid frequency, no oscillation caused by the mismatching of the prime mover and load, and no overspeed. Therefore, no need to configure the out-of-step protection, frequency protection and reverse power protection .

3. The synchronous condenser has the ability of synchronous operation without excitation, frequency conversion startup process, and exists the risk of asynchronous impulse, the breaker failure protection cannot operate when being initiated by non-whole-phase protection. Therefore, the unique loss of excitation protection, frequency conversion startup process protection, low-voltage decoupling protection and fast de-excitation after the non-whole-phase fault should be configured. Meanwhile, based on the special startup and operation mode of the synchronous condenser, the protection scheme and function enabled strategy are put forward.

KEYWORDS

HVDC; Synchronous Condenser; Loss of Excitation Protection; Frequency Conversion Startup Process Protection; Low-voltage Decoupling Protection; Fast De-excitation

1 INTRODUCTION

The energy distribution and power load center of China are extremely unbalanced. The hydropower resources are mainly concentrated in the southwestern provinces. The coal resources are mainly concentrated in Shanxi province, Shaanxi province and western Inner Mongolia, while the eastern coast region is power load center as a result of the developed economy^[1].

In order to solve the problem of energy distribution imbalance in China, HVDC transmission technology has been widely used to realize asynchronous power grid interconnection in different regions. The DC converter station needs to consume a large amount of reactive power, which was mainly provided by static var compensator and static var generator^[2]. However, when the grid voltage is reduced, the static var compensator and static var generator cannot achieve full reactive power output, but the condenser excitation system can automatically regulate and implement mandatory excitation, and continuously provide reactive power to the system. In addition, the new synchronous condenser not only meets the demand for steady reactive power, but also provides transient dynamic reactive power support, suppresses voltage fluctuations and reduces the probability of commutation failure in HVDC, which is of great significance to improve the voltage stability of the UHV AC and DC hybrid power grid, therefore it has been widely applied in DC converter stations^[3-5].

In order to ensure the safe and stable operation of the new synchronous condenser, this paper analyzes the operating characteristics of the new synchronous condenser, studies on the difference between the new synchronous condenser protection and the same capacity generator protection, puts forward the protection scheme and function enabled strategy. Due to the synchronous condenser has the ability of synchronous operation without excitation, frequency conversion startup process, and exists the risk of asynchronous impulse, the breaker failure protection cannot operate when being initiated by non-whole-phase protection. Therefore, the unique loss of excitation protection, frequency conversion startup process protection, low-voltage decoupling protection and fast de-excitation after the non-whole-phase fault should be configured.

2 CHARACTERISTICS OF THE CONDENSER

2.1 The Starting Process of the New Synchronous Condenser

The synchronous condenser cannot start on its own, and is usually started by the Static Frequency Converter (SFC)^{[6] [9]}. During the starting process, the frequency value ranges from 0Hz to 52.5Hz. The maximum stator current is about 20% rated current, and the maximum stator voltage is about 10% rated voltage. The U / F value ranges from 0 to 0.5^[10]. When the synchronous condenser is dragged from static to 1.05 times the rated speed, the SFC is disconnected, the voltage is increased to the rated value by the excitation system, and then the synchronous condenser will be synchronously interconnect to the power grid. The synchronous condenser has no prime mover, after connecting to the power grid, it absorbs a small amount of active power to maintain the rated speed and simultaneously generates or absorbs reactive power.

2.2 The Difference Between the Condenser Protection and the Generator Protection

During the starting process, all electrical quantities are frequency-variable and includes high harmonic components, so measures to prevent the regular protection maloperation should be taken. The maximum stator current is about 20% rated current, the differential alarm setting and the differential startup setting have been achieved. At this point, the differential protection should be exited. In addition, based on the power frequency calculation, the negative sequence overcurrent protection setting of the synchronous condenser is generally set 8% to 10% of the rated current. In order to prevent protection from maloperation, it should also be exited.

The third harmonic voltage ratio protection is composed of the third harmonic voltage of generator terminal and the third harmonic voltage of neutral point side. During the low-frequency startup process, considering that the neutral point of the synchronous condenser may need to be opened, and the third harmonic voltage ratio cannot be accurately calculated, the third harmonic voltage ratio protection should be exited. The stator earth-fault protection with voltage injection is achieved based on the 20Hz voltage, and the startup process pass 20Hz, which may cause the calculation to be incorrect due to frequency aliasing, so it should also be exited.

The settings of the voltage controlled overcurrent protection are based on the Fourier algorithm of the power frequency. In the process of low-frequency start-up, the calculation error of voltage value and current value is large^[7-8].

The stator earth-fault protection and the inter-turn protection are affected by frequency. Because the voltage during the starting process is low, the zero-sequence voltage is set higher according to the state of the condenser connected to the grid. Therefore, the protection ranges of the stator earth-fault protection and the inter-turn protection are extremely small. The stator earth-fault protection and the inter-turn protection should be exited.

In order to reflect the stator phase-to-phase short circuit and stator earth-fault of the condenser in the startup process, it is necessary to supplement the frequency conversion startup process protection. Because the stator voltage frequency is very low, many protective characteristics are greatly affected by the frequency. Such as some protections cannot operate at all, some sensitivities are greatly reduced. So the protections need to adopt the algorithm not affected by the frequency, and the low frequency differential protection and low frequency overcurrent protection should be configured to solve the phase-to-phase fault, and low-frequency zero-sequence voltage protection to solve the stator ground fault.

The synchronous condenser has no prime mover, after connecting to the power grid, it absorbs a small amount of active power to maintain the rated speed and simultaneously generates or absorbs reactive power. There is no oscillation caused by the mismatch between the prime mover and the power load, and there is no overspeed. Therefore, the out-of-step protection, the reverse power protection and the frequency protection should be exited.

The synchronous condenser can still maintain synchronous operation after loss of excitation, there is no loss of static stability and out-of-step. The conventional principle of the loss of excitation protection cannot be adapted to the operation mode of the synchronous condenser. The protection should employ the combination criteria of system low voltage, terminal low voltage, rotor low voltage and reactive power, to reflect the characteristics of reactive power and voltages.

When the grid is powered again in the case of loss power, to prevent the synchronous condenser from possible damage of asynchronous impulse overcurrent, the low-voltage decoupling protection should be configured.

3 THE PROTECTION FUNCTION SCHEME IMPLEMENTATION

3.1 The Protection Function Scheme

The protection configuration of the new synchronous condenser is similar to the protection configuration of the same capacity generator. The following principles should also be observed:

(1)The stator earth-fault protection is better to adopt two different principle configuration schemes. One is the fundamental zero-sequence overvoltage protection and third harmonic voltage ratio protection; the other is the stator earth-fault protection with voltage injection.

(2)The rotor earth-fault protection is better to adopt two different principle configuration schemes. One is the rotor earth-fault protection with Ping-pang type; the other is the rotor earth-fault protection with voltage injection.

(3)The frequency conversion startup process protection includes the low frequency differential protection, the low frequency overcurrent protection and the low frequency zero-sequence voltage protection. The low frequency differential protection and low frequency overcurrent protection should be configured to solve the phase-to-phase fault, and low frequency zero-sequence voltage protection to solve the stator ground fault.

The protection function scheme is shown in Table 1 below:

NO	Protection Function	NO	Protection Function
1	Condenser Differential Protection	8	Negative-sequence Overload Protection
2	Condenser Inter-turn Protection	9	Loss of Excitation Protection
3	Voltage Controlled Overcurrent Protection	10	Overvoltage Protection
4	Stator Earth-fault Protection	11	Over-excitation Protection
5	Stator Earth-fault Protection with Voltage Injection	12	Frequency Conversion Startup Process Protection
6	Rotor Earth-fault Protection	13	Inadvertent Energization Protection

Table 1: Protection Function Scheme Table

3.2 Protection Function Enabled Strategy

The condenser is a special type of synchronous motor that absorbs a small amount of active power to maintain the rated speed and simultaneously generates or absorbs reactive power. The condenser is started by the SFC, which is dragged from the static to 1.05 times the rated speed. The startup process is special. After the condenser is paralleled in the power grid, the reactive power is absorbed or generated. The operation mode is special. Therefore, the protection function enabled strategy is special.

The protection function enabled strategy is shown in Table 2.

NO	Protection Function	startup process	paralleled in the grid
1	Condenser Differential Protection	exited	configured
2	Condenser Inter-turn Protection	exited	configured
3	Voltage Controlled Overcurrent Protection	configured	configured
4	Stator Earth-fault Protection	exited	configured
5	Stator Earth-fault Protection with Voltage Injection	exited	configured
6	Rotor Earth-fault Protection	configured	configured
7	Stator Overload Protection	configured	configured
8	Negative-sequence Overload Protection	exited	configured
9	Loss of Excitation Protection	exited	configured
10	Oversvoltage Protection	configured	configured
11	Over-excitation Protection	configured	configured
12	Frequency Conversion Startup Process Protection	configured	exited
13	Inadvertent Energization Protection	configured	configured
14	Low-voltage Decoupling Protection	exited	configured

Table 2: Protection Function Enabled Strategy

(1) In the startup process, the condenser differential protection should be exited. The condenser differential protection is composed of the currents of terminal and neutral point, and the differential current calculation is based on the power frequency Fourier algorithm. The frequency is very low, there is the current transformer error, and the power frequency algorithm has a large error in the calculation of the low-frequency component, which is likely to cause errors in the calculation of the condenser terminal and neutral point, causing protection misoperation.

(2) The third harmonic voltage ratio protection is composed of the third harmonic voltage of generator terminal and the third harmonic voltage of neutral point side. During the low-frequency startup process, considering that the neutral point of the synchronous condenser may need to be opened, and the third harmonic voltage ratio cannot be accurately calculated, the third harmonic voltage ratio protection should be exited.

(3) The stator earth-fault protection with voltage injection is achieved based on the 20Hz voltage, and the startup process pass 20Hz, which may cause the calculation to be incorrect due to frequency aliasing, so it should also be exited.

(4) In the startup process, the condenser is disconnected with the power grid. The low-voltage decoupling protection should be exited.

(5) In the startup process, the negative sequence current protection based on the power frequency calculation calculates a large negative sequence component, which is easy to cause protection misoperation. So the negative-sequence overload protection should be exited.

(6) When the condenser is paralleled in the grid, the frequency conversion startup process protection should be exited. Because it only reflects the stator phase-to-phase short circuit and stator earth-fault of the condenser in the start-up process.

3.3 Loss of Excitation Protection

The condenser is normally operated under over-excitation or under-excitation conditions. It absorbs a small amount of active power to maintain the rated speed and simultaneously generates or absorbs reactive power.

It is assumed that the condenser is connected to the infinite capacity power bus by the system contact reactance. In general, the steady-state expressions of active and reactive power at the bus are:

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$$\left. \begin{aligned} P_s &= \frac{E_0 U_s}{X_{d\Sigma}} \sin \delta + \frac{U_s^2}{2} \left(\frac{1}{X_{q\Sigma}} - \frac{1}{X_{d\Sigma}} \right) \sin 2\delta \\ Q_s &= \frac{E_0 U_s}{X_{d\Sigma}} \cos \delta - \frac{U_s^2}{X_{d\Sigma}} - U_s^2 \left(\frac{1}{X_{q\Sigma}} - \frac{1}{X_{d\Sigma}} \right) \sin^2 \delta \end{aligned} \right\}$$

$$\begin{aligned} X_{d\Sigma} &= X_d + X_s \\ X_{q\Sigma} &= X_q + X_s \end{aligned}$$

In the formula:

δ —power angle;

X_s -- system contact reactance;

U_s -- system voltage;

X_d 、 X_q -- d-reactance and q-reactance.

For the non-salient pole condenser, if X_d is equal to X_q , the synchronous power P_s acting on the motor shaft is equal to 0 when the excitation is lost. Due to the existence of active loss, the slip occurs between the rotor and stator of the condenser. The condenser works under asynchronous operation condition. Since there is no load, the slip of the condenser is very small. After the condenser is turned into asynchronous operation, the reactance presented becomes smaller, theoretically between the subtransient reactance and the d-reactance. In fact, because the slip is small, the reactance presented is much larger than the subtransient reactance, and close to d-reactance. Therefore, the maximum reactive power that may be absorbed is slightly larger than $Q_s = \frac{U_s^2}{X_{d\Sigma}}$.

For an actual non-salient pole condenser, the rotor cannot be completely symmetrical, so X_d cannot be equal to X_q , and the non-salient pole condenser always has a certain amount of reaction torque.

On the other hand, the active power loss of the condenser is very small, generally not exceeding 1% to 2% of the rated power. Therefore, when the excitation is lost, the non-salient pole condenser cannot be out-of-step, and the maximum reactive power absorbed is also determined by the d-reactance.

The schematic diagram of the loss of excitation fault is shown in the below figure:

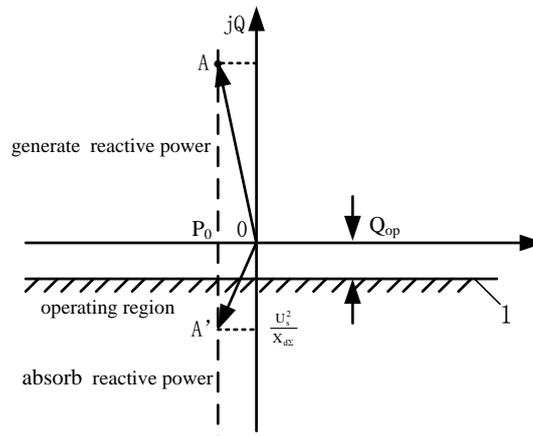


Figure 1: Schematic Diagram of the Loss of Excitation

The active loss (P_0) of the condenser is small, if the normal output reactive power is Q_n , its operating point is point A in the second quadrant of the above picture. When the excitation is lost, if the active loss (P_0) of the condenser is kept basically the same, and it can keep running synchronously by the reaction power, the working point A of the condenser will be moved along the straight line

from the second quadrant to the A' of the third quadrant. At this point, the reactive power absorbed by the system is approximately $Q_s = \frac{U_s^2}{X_{d\Sigma}}$.

Therefore, for a large non-salient pole condenser, the loss of excitation fault is not dangerous to the condenser itself. The hazard is mainly due to the system losing an amount of reactive power, causing the system voltage to drop. If the system has insufficient reactive power reserve, it may damage the stable operation of the power system. Therefore, in the loss of excitation protection, there must be components that monitor the voltage. Generally, the inverse reactive power criterion and the terminal undervoltage criterion are used to ensure the safety of the power system and the operation is shutdown; the inverse reactive power criterion and the rotor-side undervoltage criterion are used to ensure the safety of the condenser and the operation is also shutdown.

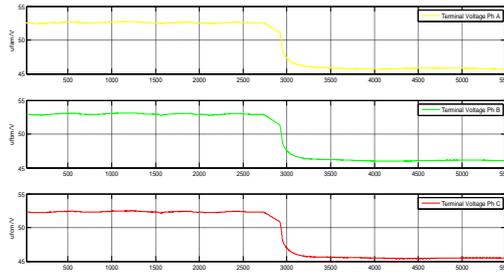


Figure 2: Terminal Voltage Amplitude Waveform

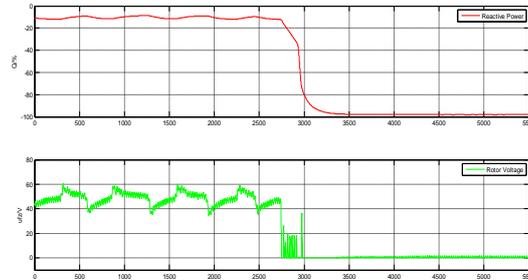


Figure 3: Inverse Reactive Power and Rotor-Side Voltage Waveform

3.4 Frequency Conversion Startup Process

The synchronous condenser has no prime mover. It cannot start on its own, and usually is started by the asynchronous motor and the static frequency converter (SFC). The asynchronous motor startup mode is to install the asynchronous motor coaxially in the condenser. The condenser is dragged by the asynchronous motor from static to 1.05 times the rated speed, and then paralleled in the grid. The variable frequency startup mode is to use the static frequency converter (SFC) to drag the condenser to start. The asynchronous motor startup mode is generally used for the small capacity condenser. The large capacity condenser requires more motor startup power. The coaxial installation is difficult. Therefore, the large capacity condenser is usually started by the static frequency converter (SFC). This variable frequency startup mode has the advantages of no need for coaxial installation, one-to-many startup, and small impact on the power grid.

During the startup process by SFC, the stator voltage frequency is very low, and many protective characteristics are greatly affected by the frequency. Such as some protections cannot operate at all, some protection sensitivities are greatly reduced. So the protections need to adopt the algorithm not affected by the frequency. In addition, the amplitude error and phase error of the voltage transformer are small at the low frequency operation, and the influence of frequency variation can be ignored. But the error of the current transformer will increase with the decrease of the frequency, and the reliability of protection at extremely low frequency needs to be considered. Therefore, the low frequency differential protection and low frequency overcurrent protection should be configured to solve the phase-to-phase fault, and low frequency zero-sequence voltage protection to solve the stator ground fault.

3.5 Low-voltage Decoupling Protection

When the synchronous condenser is paralleled in the power grid, the entire DC converter station loses power due to external faults or other reasons, the synchronous condenser cannot disconnect with

the grid since the fault is not in its protection range. When the grid is powered again in the case of loss power, to prevent the synchronous condenser from possible damage of asynchronous impulse overcurrent, the low-voltage decoupling protection should be configured. It adopts criteria of lower phase-to-phase voltage and grid-connected breaker state, and also the voltage drop process is considered comprehensively.

The schematic diagram of the low-voltage decoupling protection is shown in the below figure:

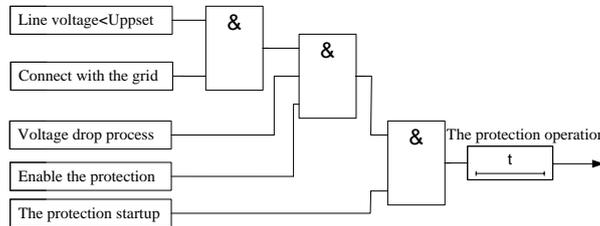


Figure 4: Schematic Diagram of the Low-voltage Decoupling Protection

3.6 Non-whole-phase Protection

The normal operation of the synchronous condenser is generally with no-load or light-load. The breaker failure protection adopts electrical quantity and the non-whole-phase protection action contact. If non-whole-phase fault happens to the grid-connected breaker, the breaker failure protection fails to remove the fault because of the tiny fault current, the negative sequence current may cause damage to the rotor.

In engineering application, the capacity of the synchronous condenser is 300 Mvar, the primary rated current of the synchronous condenser is 8660A, the CT ratio of the terminal of the synchronous condenser is 12500/5, the CT ratio of the main transformer's high-voltage side non-whole-phase protection is 1000/1, and the CT ratio of the breaker failure protection is 2000/1. The protection settings of non-whole-phase protection and the breaker failure protection are as follows:

The non-whole-phase protection zero-sequence current is set at 100A, the negative-sequence current is set at 100A, and the protection operation time is 0.10s.

The breaker failure protection zero-sequence current is set at 200A, the negative-sequence current is set at 100A, and the protection operation time is 0.25s.

For the non-whole-phase fault of the synchronous condenser, 0Mvar single phase non-whole-phase fault experiment, 0Mvar two phase non-whole-phase fault experiment, 150Mvar single phase non-whole-phase fault experiment, 150Mvar two phase non-whole-phase fault experiment were conducted. Record the maximum value of the negative sequence current of the high voltage side of the main transformer, the maximum value of the zero sequence current of the high voltage side of the main transformer, and the maximum value of the negative sequence current of the synchronous condenser. The experimental results were as shown in Table 3.

Experiment	0Mvar single phase	0Mvar two phase	150Mvar single phase	150Mvar two phase
Transformer negative sequence current	7A	9A	38A	62A
Transformer zero sequence current	41A	27A	234A	187A
Terminal negative sequence	176A	276A	1041A	1656A

Table3: Primary Current Data of the Non-whole-phase Fault Experiment

According to the 0 Mvar non-whole-phase fault experiment, the zero-sequence and negative-sequence components in the fault current of the high voltage side of the main transformer are very small, and the breaker failure protection cannot operate. The non-whole-phase protection of the protection device cannot operate because of the small zero-sequence and negative-sequence components in the fault current of the high voltage side of the main transformer. At this time, the negative sequence current of the synchronous condenser is much smaller than the long term allowable negative sequence current (866A), which has little damage to the synchronous condenser and the synchronous condenser can be selectively shut down.

Comparing the data of the experiments of 0Mvar and 150Mvar, the zero sequence of the main transformer and the negative sequence current of the high voltage side of the main transformer increase with the increase of the load current of the synchronous condenser, and the characteristics of

the zero sequence current component in the fault current are obvious. The negative sequence current of the synchronous condenser also increases with the increase of the synchronous condenser load current, and exceeds the long term allowable negative sequence current(866A).It has large damage to the synchronous condenser and the synchronous condenser should be shut down.

The data of the 150 Mvar non-whole-phase failure experiment shows that the zero-sequence current criterion of the breaker failure protection is satisfied. When the breaker failure protection receives the non-full-phase protection action contact, the breaker failure protection removes the fault.

However, the normal operation of the synchronous condenser is generally with no-load or light-load and the non-full-phase fault occurs under different loads, the fault current value of the breaker failure protection does not necessarily meet the operating conditions, which makes the breaker failure protection unable to remove the fault. In order to solve this problem, the fast de-excitation solution after non-whole-phase fault is proposed, that is tripping the de-excitation breaker to make the synchronous condenser in loss of excitation situation, thereby increasing the fault current to make sure the breaker failure protection can operate and remove the fault.

For the fast de-excitation solution after non-whole-phase fault of the synchronous condenser,0Mvar single phase non-whole-phase fault experiment, 0Mvar two phase non-whole-phase fault experiment, 150Mvar single phase non-whole-phase fault experiment, 150Mvar two phase non-whole-phase fault experiment were conducted. Record the maximum value of the negative sequence current of the high voltage side of the main transformer, the maximum value of the zero sequence current of the high voltage side of the main transformer, and the maximum value of the negative sequence current of the synchronous condenser .The experimental results were as shown in Table 4.

Experiment	0Mvar single phase	0Mvar two phase	150Mvar single phase	150Mvar two phase
Transformer negative sequence current	59A	138A	58A	131A
Transformer zero sequence current	371A	415A	361A	393A
Terminal negative sequence	1594A	3720A	1547A	3490A
Time withstanding negative sequence current	422.46s	57.37s	460.78s	65.70s

Table4: Primary Value of Fast De-excite Experiment in Non-whole-phase Fault

By comparing the single phase non-whole-phase fault experiment of 0Mvar with that of 150Mvar, the two phases non-whole-phase fault experiment of 0Mvar and 150Mvar, it can be seen that the negative sequence current and zero sequence current at the high voltage side of the main transformer increase significantly. The breaker failure protection can operate and remove the fault. There is little difference in the negative sequence current and zero sequence current of the high voltage side of the main transformer under different power loads. And there is also little difference in the negative sequence current of the synchronous condenser under different power loads. It indicates that the final fault current of fast de-excite experiment is independent of the power loads of the synchronous condenser before the de-excitation switch is tripped, and only related to the faulty phases of non-whole-phase fault.

Through theoretical analysis and experimental verification, the fast de-excitation solution after non-whole-phase fault, can increase the fault current at the high voltage side of the main transformer, and the breaker failure protection can fast remove the fault. However, the negative sequence current of the synchronous condenser will also increase and exceed the long term allowable negative sequence current. It has damage to the synchronous condenser and the synchronous condenser should be shut down quickly.

4 CONCLUSION

The new synchronous condenser not only meets the demand for steady reactive power, but also provides transient dynamic reactive power support, suppresses voltage fluctuations and reduces the probability of commutation failure in HVDC. This paper analyses the operation characteristics of the synchronous condenser, compares the differences between the synchronous condenser and the synchronous generator, and studies on the particularity of the protection function. The synchronous condenser has the ability of synchronous operation without excitation, and frequency conversion startup process. It exists the risk of asynchronous impulse, and the breaker failure protection cannot operate when being initiated by non-whole-phase protection. Therefore, this paper configures the

unique loss of excitation protection, frequency conversion startup process protection, low-voltage decoupling protection and fast de-excitation after the non-whole-phase fault. Meanwhile, this paper puts forward the protection scheme and function enabled strategy based on the special startup and operation mode of the synchronous condenser.

Based on the research results of this paper, the protection devices of the new synchronous condenser have been developed in five DC converter stations such as Xiangtan Converter Station, Taizhou Converter Station and Nanjing Converter Station, etc. Eleven protection devices have been connected to the power grid, and the longest operating time of the protection devices has exceeded 17 months. The protection devices operate well and have many times correct fault action, which ensure the safe and stable operation of the condenser.

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