The Influence of Multi-terminal MMC-HVDC on the Subsynchronous Oscillation Characteristics of the Unit

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Abstract. The five-terminal MMC-HVDC in Zhoushan can bring the risk of SSO to the units in the neighbouring Zhoushan power plant. This paper illustrates the five-terminal MMC-HVDC on the topology structure and the working principle of the three-layer control system (the system level, the convert level and the valve level, etc.); the shaft multi-mass model of steam turbine generator in the Zhoushan power plant is established, too. Finally, the simulation model based on the actual power grid in Zhoushan area is established in the RTDS, and the influence of different control methods and operation modes on SSO characteristics of Zhoushan power plant unit is analyzed. This paper reveals the influence of different control methods on SSO characteristics of the units, and the influence of different operation modes on the initial values of the SSO modal

Introduction

Due to Modular Multilevel Converter based High Voltage DC (MMC-HVDC) technology using fully controlled power electronic device and flexible control system, it has lots of advantages such as flexible operation modes, independent active and reactive power decoupling control, functioning without reactive power compensation equipment, supplying power to the weak AC system, reversing flow without changing the voltage polarity and significantly improving the voltage stability of AC system. Therefore, it has significant advantages in the renewable energy grid interconnection, distributed power generation interconnection, island power supply, new energy consumption, large city power supply and so on[1-2].

Power system sub-synchronous oscillation (SSO) is a kind of electromechanical coupling oscillation phenomenon between the transmission network and generators[3]. The turbine generator shaft system vibration will be excited when SSO occurs, which will cause the shaft fatigue damage even the destruction. The existing researches have proved, that the power electronic device with fast response characteristic such as LCC-HVDC, PSS, SVC and so on, have a potential risk of causing SSO in the adjacent turbine generators[4]. As the power electronic devices with fast control, there is also the possibility for MMC-HVDC system to cause SSO in the adjacent generators.

Most of the existing literatures focus on the impact of LCC-HVDC on SSO characteristics[5], which believes the LCC-HVDC control system and the generator shaft will form a negative feed-back loop, causing SSO risk in the units, when the control parameters are improperly set. However, due to the difference of the topologies and the control principles between LCC-HVDC and MMC-HVDC, the existing mechanism has limitations on revealing the influence of MMC-HVDC on the SSO characteristics.

At present, the literatures related to the influence of MMC-HVDC on the SSO characteristics of the units mainly provide two ideas: In [6-8], MMC-HVDC is simplified into a rigid load with damping effect on the active power oscillation, which is considered to suppress the SSO, but this analysis method and the conclusions are too coarse without considering the influence control system. In [9], the equivalent simulation model composed of controlled voltage and current source instead of MMC-HVDC and its control system is set to study the impact of MMC-HVDC on the SSO
characteristics of units with the test signal method, but the conclusions is not of high credibility because of the model’s low accuracy.

In [10-12], both the test signal method and the eigenvalue method are used to analyze the electronic de-vices with similar dq decoupling control structure such as STATCOM, FACTS, two or three-level VSC-HVDC, etc. Under different control modes and control system parameters, the SSO damping characteristics of units are study, but the impact mechanism of these devices with fast control system on SSO characteristic of units is not revealed in the physical plane.

In this paper, the influence of control system and operation modes of MMC-HVDC on SSO characteristics of the units is studied. Firstly, the working principle and the three-layer control system of MMC-HVDC are analyzed and illustrated. Furthermore, the mechanism of generator shaft torsional vibration is analyzed. At last, the simulation model of Zhoushan five-terminal MMC-HVDC and Zhoushan power plant is established in RTDS. The time-domain simulation method is used to analyze the influence of the operation modes and system parameters of five-terminal MMC-HVDC on the SSO characteristics of units under small disturbance and large disturbance.

The Basic Principles of MMC-HVDC

The Working Principle of MMC-HVDC Converter

As the structures of the MMC-HVDC converters are basically the same, the working principle of the converts are illustrated by taking one-terminal converter as an example. An MMC converter consists of six arms with N submodules and one bridge arm reactor \( L \) in series to form each bridge arm, which is shown in Fig 1. And each submodule is formed with an H-bridge consisting of two insulated gate bipolar transistors (IGBTs) with inverted parallel diodes and one capacitor in parallel\(^{[13]}\), as shown in Fig 1.

\( U_s, U_c \) and \( U_d \) are respectively the AC bus voltage, the inverter AC output voltage and DC voltage, and \( L \) is the filter reactance, ignoring the filter resistance.

![Figure 1. The topology of MMC-HVDC converter and submodule.](image)

According to the different switch states of IGBTs in the submodule, the basic working states of each submodule are generally divided into three types: blocking, output voltage is 0 and the output voltage is \( U_{SM} \). As the sum of the submodule output voltage in each arm determines the total voltage of each arm, supposed that the voltages of the upper and lower arms per phase are respectively \( U_{ip} \) and \( U_{in} \), and the AC output voltage per phase is \( U_{ci} \), where \( i = a, b, c \).

In order to keep the DC voltage constant, there should be:

\[
U_{ip} + U_{in} = U_d = constant
\]  

(1)

Assuming that the number of submodules whose output voltage \( U_{SM} \) equals \( U_c \) (\( U_c \) is constant under steady state) in the upper and lower arms per phase is respectively \( N_{ip} \) and \( N_{in} \), it should be satisfied at any time:

\[
N_{ip} + N_{in} = N
\]  

(2)
At the same time, the AC output voltages per phase obtained from the Kirchhoff law should be:

\[ U_{ci} = 0.5(U_{in} - U_{ip}) \]  

(3)

In order to ensure the AC output voltages three-phase sinusoidal, it is necessary to control submodule IGBTs switch state. Then at any time it should be satisfied

\[ (N_{in} - N_{ip}) = 2U_{ci}/U_C \]  

(4)

Since \( U_{ci} \) is given at any time, \( N_{ip} \) and \( N_{in} \) can be computed at any time, too.

The Control Principle of Multi-terminal MMC-HVDC

The multi-terminal MMC-HVDC system control system can be divided into three layers: system-level control, converter-level control and valve-level control[13].

(1)System-level control is the most advanced control of MMC-HVDC, responsible for coordinating the power balance between different converters, maintaining the DC voltage constant and transmitting the active and reactive physical reference value to the subordinate control system.

(2)Converter-level control is responsible for generating the voltage reference value at the converter’s AC side, according to active and reactive physical reference value transmitted from the system-level control.

(3)Valve-level control ultimately generates a constant DC voltage and three-phase sinusoidal AC voltages, according to AC voltage reference value from converter-level control.

System-level control will again carry out coordinated control in accordance with DC voltage and AC voltage generated by valve-level control. Therefore, the three-layer control system constitutes a closed-loop with mutual cooperation layer by layer to control multi-terminal MMC-HVDC, and ultimately realize the safe and stable operation of the system.

The Torsional Vibration Characteristics of Turbine Generator Shaft System[14]

The Torsional Vibration Phenomenon of Turbine Generator Shaft System

In 1970 and 1971, the shaft damage occurred twice in the United States Mohave power plant. The power industry and academia revealed that the phenomenon is caused by the series compensation capacitor, called "mechanical torsional vibration interaction". That is, the electrical system LC resonance will stimulate the torsional vibration instability of generator shaft system under certain conditions. With the deepening of the re-search, it is found that some other devices with fast control system such as power system stabilizer (PSS), static reactive power compensator (SVC) and HVDC system control system may cause the generator shaft torsional vibration, too.

At present, the SSO in power system often refers that when the turbine generator unit is disturbed at the operating point, the electrical system and the turbine generator have significant energy exchange at one or more frequencies below the system synchronization frequency, which does not include the rigid-body oscillation mode of the rotor-shaft system, thus jeopardizing the safe operation of the turbine generators’ shafts.

The Multiple Mass Block Model of Turbine Generator Shafting

In the low-frequency oscillation analysis study, the generator shaft is analyzed as a rigid body. In fact, because high-pressure cylinder, intermediate pressure cylinder, low-pressure cylinder, generator rotor and exciter are jointly connected to the generator turbine shaft system, the total length of the shaft are more than 50 meters which lets the shaft system contain a plurality of natural torsional vibration frequencies.

In the study of SSO, the centralized mass block model is used because of the focus on oscillation frequency band (5-40Hz), that is to say that the shaft system is expressed as the structure composed of N mass blocks connected by means of no mass springs, which is similar with the actual shaft.
structure. Because of the simplicity and the clear physical concept of the centralized quality model, it is commonly used in practical engineering.

In general, turbine generator shafting can be divided into six shaft segments, each of which is treated as an equivalent rigid centralized mass. These masses are connected by a massless spring to simulate the torque transmission relationship between masses. Suppose there are $N$ concentrated mass blocks in the generator shaft, as shown in Fig. 2, where MASS1, MASS2, and MASSN represent the first, second, and $N$th mass masses, respectively.

![Figure 2. The illustration of the shafting multiple mass blocks.](image)

The multi-mass block model equations for the generator shaft system shown in the above figure can be expressed as follows:

$$(M_p^2 + Dp + K)\Delta \delta = \Delta T$$

(5)

Where $M$, $D$ and $K$ are the inertia time constant, damping and the elastic coefficient between masses. The characteristic roots of N-1 group and their corresponding right eigenvectors can be solved in matrix $M^{-1}K$ without considering the damping ($D = 0$), where the characteristic roots represent the oscillation frequencies and the corresponding right eigenvectors represent oscillation amplitudes and phases at each frequency, which are collectively referred to as the mode shapes.

Thus in general, there are N-1 torsional modes (characterizing the torsional modes between masses) and a cylinder block mode (characterizing the low frequency oscillation mode of generator related to the system as the shaft is a rigid body), when there are N mass blocks in the shafting mass block model of the generator.

Taking the shafting parameters of #4 unit in Zhoushan power plant as an example, the shafting parameters of #4 unit are listed in Table 1, where $M_i (i = 1, 2, 3)$ is the inertia time constant of the mass block and $K_{ij} (i = 1, 2)$ is the elastic coefficient parameter between the first and the second mass. The torsional vibration’s vibration-types diagram of #4 in Zhoushan power plant can be obtained, which is shown in Figure 3.

![Figure 3. The torsional vibration vibration-type diagram of #4 in Zhoushan power plant.](image)

Table 1. The shafting parameters of #4 in Zhoushan power plant.

<table>
<thead>
<tr>
<th>$M_1$ (kg*m²)</th>
<th>$M_2$ (kg*m²)</th>
<th>$M_3$ (kg*m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4697.53</td>
<td>31622.295</td>
<td>7310.525</td>
</tr>
<tr>
<td>$\kappa_{ij}$ (N*m/rad)</td>
<td>$\kappa_{ij}$ (N*m/rad)</td>
<td></td>
</tr>
<tr>
<td>88293000</td>
<td>99280400</td>
<td></td>
</tr>
</tbody>
</table>

It can be seen from Figure 3, when SSO occurs, there is no phase reversal from the high-pressure cylinder to the low-pressure cylinder and a phase reversal from the low-pressure cylinder to the generator with high amplitude of the vibration under modal I. While there is a phase reversal from the high-pressure cylinder to the low-pressure cylinder and no phase reversal from the low-pressure cylinder to the generator under modal II. From the above, it can be concluded that the shaft system of #4 unit has the risk of continuous torsional vibration in the case of negative damping, and if the
external disturbance occurs, the torsional vibration with higher amplitude may be excited which will cause shaft damage.

Therefore, the multi-mass block model can be used to study the influence of multi-terminal MMC-HVDC on the SSO characteristics of the turbine generator, which is used to describe the dynamical process of generator rotor shaft system when disturbed.

**The Risk Analysis of SSO in Zhoushan Power Plant**

**The Parameters of the Study System and the Modeling Methods**

Figure 4 has shown the Zhoushan five-terminal MMC-HVDC, which was formally completed and put into operation in 2011. It adopts the modular multi-level HVDC (MMC-HVDC) system, and its DC voltage is ±200kV. There are five stations in Dinghai, Daishan, Qushan, Yangshan, Sijiao, with the capacity of 400MW, 300MW, 100MW, 100MW, 100MW, respectively. The system-level control of the Zhoushan five-terminal MMC-HVDC is the master-slave control mode, and the Daishan station is selected as the DC voltage balance point. The reactive control can be switched between the fixed AC voltage control and the fixed reactive power control freely according to different needs. The valve-level control is NLM method with 250 submodules per arm.

![Figure 4. The simulation model system diagram of Zhoushan area.](image)

As the Zhoushan power plant has a close electrical contact with Dinghai and Daishan converters of large capacity, there may be SSO risks units in Zhoushan power plant. In order to study the influence of MMC-HVDC on the SSO characteristic, a real-time digital simulation (RTDS) system model, which presents Zhoushan five-terminal MMC-HVDC and the adjacent power plant, is established to analyze this problem, using the time-domain simulation method.

**The Influence of Control Modes on SSO characteristics of Units**

Because of the large number of converters in Zhoushan five-terminal MMC-HVDC, the complex connection of DC system and the electrical connections in the AC side between different converters, it is necessary to simplify the study system. In order to study the influence of multi-terminal MMC-HVDC control modes on the SSO characteristics of units, #4 unit of larger capacity in Zhoushan Power Plant, Dinghai and Daishan converters of larger capacity in five-terminal MMC-HVDC and the AC lines between Zhoushan Power Plant and Changzhou, between Dinghai converter and Changzhou are selected to form a simple study system, consisting of MMC-HVDC, generators and AC system.

Because the generator is not directly connected with Daishan converter station, and the control system has a certain time delay, it is considered that the control mode of Daishan converter station has little effects on the SSO characteristics of the unit. Therefore, a small disturbance (single-phase instantaneous fault via resistance transition) is set up at the generator export bus, and the influence of four different control modes on the SSO of the unit is studied. The modal waveforms of units under the fixed DC voltage control and the fixed reactive power control are shown in Figure 5, and the decay rates of modals under different four control modes are computed and listed in Table 2.
The shaft slip ratio (rad/s)

Figure 5. The modal waveforms of units under fixed DC voltage control and the reactive power control.

<table>
<thead>
<tr>
<th>Control Modes</th>
<th>Decay Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active control</td>
<td>Reactive control</td>
</tr>
<tr>
<td>Fixed Udc</td>
<td>Fixed Q</td>
</tr>
<tr>
<td>Fixed Udc</td>
<td>Fixed Uac</td>
</tr>
<tr>
<td>Fixed P</td>
<td>Fixed Q</td>
</tr>
<tr>
<td>Fixed P</td>
<td>Fixed Uac</td>
</tr>
</tbody>
</table>

Therefore from the data in Table 2, the following conclusions can be gotten:

1. In Table 2, with comparison of data in the first line and the second line, the third line and the fourth line, it can be seen that compared with the fixed AC voltage mode, mode I decays faster and mode II decays slower when the sending converter uses the fixed reactive power control.

2. In Table 2, with comparison of data in the first line and the third line, the second line and the fourth line, it can be seen that compared with the fixed active power mode, mode I and II decays faster when the sending converter uses the fixed DC voltage control.

The influence of Operation Modes on SSO Characteristics of Units

In order to study the influence of MMC-HVDC operation modes on the SSO characteristics under large disturbances, a three-phase instantaneous short-circuit fault is set in the Zhoubei 220kV bus to observe the initial value of each modal of the shaft slip ratio.

Because of Daishan converter’s hub position in the five-terminal MMC-HVDC and its larger rated power, it can be used to balance the active power in the system. Generally, the active control of Daishan converter adopts the fixed DC voltage control, thus other converters adopting the fixed active power control. The modal waveforms of #4 shaft system in Zhoushan Power Plant under the five-terminal operation mode is shown in Figure 6 (where the cyan represents the fixed active power control in all converters and the black represents the fixed AC voltage control in all converters). The initial values of the various modes of the units under different operating modes are listed in Table 3.

Figure 6. The modal waveforms of #4 shaft under the five-terminal operation mode.
Table 3. The initial value of modals under different operation modes.

<table>
<thead>
<tr>
<th>Decay rate</th>
<th>Fixed Q</th>
<th>Fixed Uac</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modal I</td>
<td>Modal II</td>
</tr>
<tr>
<td>Five terminal</td>
<td>0.6003</td>
<td>0.2843</td>
</tr>
<tr>
<td>Four terminal</td>
<td>0.5992</td>
<td>0.2842</td>
</tr>
<tr>
<td>Three terminal</td>
<td>0.6025</td>
<td>0.2780</td>
</tr>
<tr>
<td>Two terminal</td>
<td>0.6010</td>
<td>0.2923</td>
</tr>
</tbody>
</table>

Therefore from Table 3, the following conclusions can be gotten:

1. Regardless of how the operating mode changes, the modal I has a larger initial value in the fixed active power control than the fixed DC voltage control.
2. The initial value of modal II is larger in the fixed reactive power control under the five-terminal operation mode, while in other operating modes, the initial value of modal II is larger in the fixed DC voltage control.
3. Regardless of how the operating mode changes, the initial value of modal I is large which easily leads excitation in shaft continuous torsional vibration under the external disturbance, causing shaft damage.

Conclusion

In this paper, the main research work, taking the five-terminal MMC-HVDC in Zhoushan area as an example, is as follows:

1. The topology and working principle of the MMC-HVDC converter station in Zhoushan are analyzed and explained: the three-layer control system is analyzed hierarchically, including system-level, converter-level and valve-level control.
2. The generation mechanism of generator shaft torsional vibration is analyzed, the mathematical model of multi-mass block shafting of Zhoushan power plant is established, and the torsional vibration mode of #4 in Zhoushan power plant is analyzed.
3. The simulation model of RTDS is established based on the actual power grid in Zhoushan area. The influence of multi-terminal MMC-HVDC control modes and operation modes on the SSO characteristics of units in Zhoushan power plant is analyzed.

References


