Research on Application of Controllable Phase Shifter Technology in 500kV Power Grid

Peng Wei, Jiankun Liu, Qian Zhou and Ningyu Zhang

ABSTRACT

With the rapid changes in structure of grid and construction of UHV project, the grid control turn more complex. Using TCPST (controlled phase shifters) and other advanced load flow control device to solve power system planning and operation problems has broad application prospects. In order study the influence of controlled phase shifter on the security and stability of power grid, basic principles and topologies of TCPST was studied. Steady-state model of TCPST was built in BPA software, the series and shunt transformer parameters were designed. Take Jiangsu power grid as background, TCPST was applied in two scenarios where near zone of Jinsu UHVDC and channel over the Yangtze river. Application effect of TCPST was analyzed. Simulation results show: TCPST can increase section transmission capacity, solve the problem of DC power reject in small load mode also the DC power output in big load mode, reduce load losses after UHVDC bipolar blocking. For the protection of grid security and economy has a positive effect.

Keywords: controllable phase shifter (TCPST); load flow control; ultra-high voltage dc (UHVDC); bipolar blocking.

INTRODUCTION

Jiangsu Power Grid East of Shanghai, south of Zhejiang, Anhui west, is an important part of East China Power Grid. Currently, there are 10 500kV inter-provincial tie-line with Shanghai, Zhejiang, Anhui. Jiangsu power grid has built a "six vertical and five horizontal" backbone 500kV transmission grid frame[1].

According to the State Grid Corporation of UHV plan, “Thirteen Five” period, will be built in Nanjing, Jiangsu, Taizhou, Suzhou, Xuzhou, Lianyungang, a total of five UHV station, forming the East China UHV ring and northern Jiangsu UHV ring; built Shanxi Province-Nanjing, Ximeng-Taizhou, Long Bin-Xuzhou HVDC project. After the above-mentioned project is completed, the outer zone calls by the Jiangsu Power Grid power capacity will more than 56 million kilowatts. Power will present 1000, 500, 220kV three electromagnetic ring network and AC-DC hybrid complex patterns linked. Multiple levels of electromagnetic ring makes Jiangsu 500kV power flow control difficult, uneven transmission section power flow, transmission capacity limited circumstances often arise[2].
In addition, "Thirteen Five" period, with the outer wind power, photovoltaic and other random, intermittent large-scale renewable energy access, development of the electricity market, as well as some area calls (such as water and electricity DC) seasonal variations, Jiangsu 500kV power flow distribution will often fluctuate significantly, increasingly showing randomness. At different times so that the different sections are often overloaded transmission. If all the above sections to reinforce the one hand, it will lead to over-investment in the power grid, reducing the company's operating efficiency, on the other hand will make the problem already exists 500kV short circuit current is difficult to control more serious.

It is seen in the UHV AC and DC reject into Jiangsu, wind power and other renewable energy sources as well as large-scale access to short-circuit current of Jiangsu 500kV grid control increasingly difficult backdrop, Jiangsu 500kV grid installation TCPST and other advanced flow control means to improve the controllability of power flow, thus ensuring the safe and stable operation and efficient power development has become a more attractive option.

FUNDAMENTAL OF TCPST

Amplitude of the voltage across the line, the voltage phase angle, line impedance determines the transmission of active power transmission lines. In Figure 1, the TCPST is installed in series as shown in the line at the installation point of a series compensation voltage output line, by adjusting the voltage amplitude or phase angle installation point, to change the power flow of distributed transmission line[3].

Ignore circuit resistance, after the installation phase shifter circuit active power is shown in (1):

\[
P = \frac{V_S V_L}{X} \sin(\phi_S + \Delta \phi - \phi_L)
\]

Where: \( V_S \), \( V_L \) is bus voltage; \( \phi_S \), \( \phi_L \) is bus voltage phase angle; \( V'_S \) is phase-shifted line voltage compensated; \( \Delta \phi \) is phase shifter phase shift angle; \( P \) is active power of transmission lines; \( X \) is the line impedance.

TOPOLOGY OF TCPST

Hierarchical Switching Type TCPST

A hierarchical switching voltage structure mode diagram is shown in Figure 2. A total of \( n \) excitation transformer windings, each winding with a group of antiparallel connected thyristors, a total of \( n \) groups. If the voltage of all windings is \( U \), then this circuit provides a variable voltage between \( 0 \sim \pm U \), a total of \( 2n+1 \) gear, differential amplitude variation of \( U/n \). This approach requires the secondary side of the transformer
regulator leads to \( n \) taps, so there is a certain degree of difficulty of manufacturing a transformer\[4-6\].

![Figure 2. Grade Switching Voltage Regulator Type.](image)

**N-type Hierarchical Switching Type TCPST**

Figure 3 is a n-type hierarchical switching structure diagram, a total of \( n \) windings, each winding constitutes a bridge with four bidirectional thyristor valve, a total of \( n \) bridge. If the voltage of all windings and the \( U \), then this circuit provides a variable voltage between \( 0 \sim \pm U \), the differential amplitude variation of \( U/n \). This circuit configuration in each leg may be implemented either polarity of the output voltage, the windings may be bypassed\[7\].

![Figure 3. N-Type Hierarchical Switching Type Tcpst.](image)

The disadvantage of this structure is that, when the system voltage is low, due to the allocation to each of the small winding voltage will be lower, as well as existing power thyristor cannot reach the minimum requirements of the economy, and thus the effect is not ideal\[8\].

**3N-Type Hierarchical Switching Type Tcpst**

In reference \[9\], 3n hierarchical switching regulator mode, using the turns ratio of 1: 3: 9 3 times winding structure, by controlling the rated voltage of 12 different sets of TRIAC conduction group obtained 27 voltage differential. 3n-type winding structure of higher utilization valve, from the transformer production standpoint, this winding structure can effectively reduce its complexity, is relatively simple and easy to implement. Structure diagram is shown in Figure 4.
Due to continuous adjustment of the controllable phase shifter is not only difficult to control, and will string into a large number of harmonics in the grid applications recommended hierarchical adjustment TCPST, hereinafter controllable phase shifter can be especially adjusted grade controlled phase shifter[10].

PARAMETERS OF TCPST

Consider the installation of 500kV TCPST in double circuit line, installation diagram is shown in Figure 5,

![500kV Tcpst Installation Diagram.](image)

Rated current value of TCPST is taken as the 500kV line rated current value 3000A, the phase shift is taken as the maximum angle of 15 degrees. On this basis, take use of symmetrical regulated controllable phase shifters, adjusted series is ± 12 level through a three-phase power 2598.08MVA, controllable phase shifter series transformer basic parameters shown in Table I[11].

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-phase rated capacity/MVA</td>
<td>448.29</td>
</tr>
<tr>
<td>Rated voltage/kV</td>
<td></td>
</tr>
<tr>
<td>Grid side/√3</td>
<td>129.41</td>
</tr>
<tr>
<td>Valve side</td>
<td>310.58</td>
</tr>
<tr>
<td>Rated current/A</td>
<td></td>
</tr>
<tr>
<td>Grid side/√3</td>
<td>3000.00</td>
</tr>
<tr>
<td>Valve side</td>
<td>1443.38</td>
</tr>
<tr>
<td>Impedance voltage</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Shunt transformers basic parameters of TCPST is shown in Table II[12].
### TABLE II. SHUNT TRANSFORMER PARAMETERS.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-phase rated capacity/MVA</td>
<td>448.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rated voltage/kV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid side/√3</td>
<td>500.00</td>
</tr>
<tr>
<td>Valve side</td>
<td>23.89</td>
</tr>
<tr>
<td>Valve side</td>
<td>71.67</td>
</tr>
<tr>
<td>Valve side</td>
<td>215.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rated current/A</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid side</td>
<td>1552.91</td>
</tr>
<tr>
<td>Valve side</td>
<td>2500.00</td>
</tr>
</tbody>
</table>

| Impedance voltage         | 0.14     |

### EFFECT ANALYSIS OF TCPST

**Over Yangtze River Channel**

"Thirteen Five" period, with the 1000kV Huainan to Shanghai UHVAC engineering southern half Central Engineering (Huainan - Xuyi - Taizhou - Suzhou - Shanghai) placement Jiangsu, Shanxi-Nanjing Province UHVDC placement Nanjing, Ximeng - Taizhou UHVDC tiered access Jiangsu, northern Jiangsu million kilowatts of wind power base, Jiangsu "North-South" power flow will increase significantly. Taking into account the UHVAC Taizhou - Suzhou over Yangtze River difficult to put into operation in 2020. At the end of "Thirteen Five", if the Northern load decreases in winter, while UHV AC and DC calls the same size, Jinsu send side dry and extreme way end hydropower and wind power in Northern, Subei "North-South" power flow will further surge in the southern unit output voltage (or down) when more Subei "North-South" power flow probably more than 15 million kilowatts, then east channel (Taixing-Doushan) flow is of about 4.37 million kilowatts, N-1, the remaining one loop current 3.53 million kilowatts, more than the thermal stability limit of about 380,000 kilowatts. In this case, the power flow over the river channel there are large margin.

Because of the new river channel is quite difficult, through the installation of TCPST to balance power flow of over river channels, enhance the "North-South" overall transmission capacity is a program that could be considered. Considered in the east river channel Taixing-Doushan installed TCPST, surrounding 500kV power grid crossing the river section and above schematic diagram shown in Figure 6.

In 2017 winter small load operation mode, according to the design phase shifter models were not installed and phase -15°, -10°, -5°, 0°, 5°, 10°, 15° this 7 stalls for four over river channels load and load rate calculation and analysis are shown in Figure 7.
Figure 6. Grid Schematic of Power Section Over Yangtze River.

Figure 7. Power of Power Section Over Yangtze River.

Line stability limit issued by the stability of the East China currently limits Sancha-Qinhuai section stability limit 2.1 million kilowatts, Sancha-Longwang section 2.1 million kilowatts, Jiangdu-Jinling section 2.5 million kilowatts, Taixing-Doushan section 2.8 million kilowatts. Four river channel over-limit rate are shown in Figure 8.

Figure 8. Over-Limit Rate of the Pass River Power Section.
When not install TCPST, Taixing-Doushan over load stable limit 510,000 kilowatts, but this time, there is still some margin for other river channel, Sancha-Qinhuai there are 110,000 kilowatts margin, Sancha-Longwang also 110,000 kilowatts margin, Jiangdu-Jinling also 510,000 kilowatts margin. Installation TCPST at phase angle about 5°, can eliminate Taixing-Doushan over load circumstances, while the other section of the river can run in a stable limit. The voltage across the TCPST during adjust process is shown in Table III.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fault location</th>
<th>Remaining line power/MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Before installation</td>
</tr>
<tr>
<td>Wujiang load peak</td>
<td>Suzhou - Wujiang N-2</td>
<td>4260</td>
</tr>
<tr>
<td>Wujiang load trough</td>
<td>Suzhou - Chefang, Wujian</td>
<td>2280</td>
</tr>
</tbody>
</table>

Load flow of Taixing-Doushan can be shifted to other river channels and mitigate Taixing-Doushan overload conditions within TCPST, especially in improving utilization of the river channel Jiangdu-Jinling, increase other river channels of North-South capacity, improve the flow distribution of the four river channels.

**UHVDC near Zone Area**

Suzhou South grid including Suzhou and Wujiang urban areas, mainly through Meili ~ Mudu, Huasu ~ Chefang and Shipai ~ Yushan ~ Chefang three 500kV transmission channel by electricity. 2020 is expected to 1000kV UHVAC Shanghai - Huainan north semiring Taizhou - Suzhou can build, then power capacity in southern Jiangsu area will be further enhanced. Southern Jiangsu grid is shown in Figure 9.

Main power of Suzhou south 500kV grid is Jinsu UHVDC (Loss deduction send full power for about 6.7 million kilowatts), since the DC power supply is hydropower, highly seasonal, summer is usually full delivery, the sending side of winter dry season power transmission significantly reduced, the minimum only 10% of the full transmission power. So that by the scale and power flow into the electricity distribution grid in southern Suzhou larger seasonal variation.

![Figure 9. Southern Jiangsu Grid.](image)

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So that by the scale and power flow into the electricity distribution grid in southern Suzhou larger seasonal variation.

**Send Questions in UHVDC Big Load**

During the 2018 summer peak load, in the case of Jinsu sent, full power, if the load is at its peak in Wujiang, Suzhou converter station - Wujiang three loops power flow are too heavy, when one of the same tower double-circuit line N-2 occurrence Suzhou Wujiang converter station–Wujiang the remaining 1 loop current to reach 4.26 million kilowatts, thermal stability than its quota; if the load in the doldrums state Wujiang, Suzhou converter station–Chefang and Wujiang–Chefang power flow will be more than 3 million kilowatts, after N-1 transmission the remaining line power flow is about 2.28 million kilowatts, exceeding its long-running limit (about 1.98 million kilowatts).

To solve the problem of Jinsu UHVDC with full power, installation of TCPST in Suzhou south 500kV grid Meili - Mudu could be considered, optimizing its power distribution.

After calculation, installed capacity of TCPST 2×200MVA (series side) + 2×200MVA (shunt side), in small load of Wujiang, Suzhou converter station–Chefang, Suzhou converter station - Chefang N-1, the power flow can be controlled to 1.64 million kilowatts, representing its operating limits (1.95 million kilowatts) there are large margin; in big load of Wujiang, can control the rest one line downward power flow 450,000 kilowatts after Suzhou converter station - Wujiang line N-2.

**Into Questions in UHVDC Small Load**

In the case of the 2018 Winter load Jinsu UHVDC under extremely small (10% output), Meili-Mudu double power flow of about 3.67 million kilowatts, after N-1 remaining loop is 3.28 million kilowatts, more than 0.33 million kilowatts stability limit (about 2.95 million kilowatts).

2020, due to the 1000kV UHVAC Taizhou–Suzhou is done, a substantial increase in Suzhou UHV transformer load down with large-scale, resulting in Suzhou the southern power grid in case of significant increase in the size of the power receiving Meili ~ Mudu power flow declined slightly (about 3.6 million kilowatts), remaining loop after N-1 is 3.19 million kilowatts, still exceeds the stability limit of 2.4 million kilowatts.

To solve the problem of Jinsu UHVDC with small power, installation of TCPST in Suzhou south 500kV grid Meili-Mudu could be considered, optimizing its power distribution.

After analysis, installed capacity of TCPST 2×200MVA (series side) + 2×200MVA (shunt side), 2018 after Meili ~ Mudu N-1 the remaining one loop is about 2.93 million kilowatts, lower than its thermal stability limit (2.95 million kilowatts); 2020 Meili ~ Mudu N-1 the remaining one loop is about 2.8 million kilowatts, lower than its thermal stability limit (2.95 million kilowatts).

**Load Shedding after Bipolar Blocking of UHVDC**

In the 2018 summer peak load, consider the case of full power for Jinsu UHVDC (direct current consideration Jin Su landing power 6.7 million kilowatts), if the occurrence of bipolar blocking, Meili-Mudu ultra-stable limit 1.2 million kilowatts (stability limit 3 million kilowatts), Huiquan-Meili ultra-stable limit 100,000 kilowatts (stability limit 3 million kilowatts). But there is still a large load margin in Shunan-Shipai-Yushan
channel, against Meili-Mudu ultra-stable limit after Jinsu UHVDC bipolar blocking, without the installation of TCPST, calculated in southern Suzhou (Mudu, Wujiang and Chefang) area shed load 1.9 million lines and the cross-sectional flow can be controlled within their stability limit.

To solve the problem of security control after Jinsu UHVDC bipolar blocking, installation of TCPST in Suzhou south 500kV grid Meili-Mudu could be considered, optimizing its power distribution.

After analysis, installed capacity of TCPST 2x200MVA (series side) + 2x200MVA (shunt side), Meili-Mudu power flow can be controlled within the stability limit, Shipai-Yushan singlet power 1.71 million kilowatts (ultra-stable limit 310,000 kilowatts), Yushan-Chefang 1.56 million kilowatts (ultra-stable limit 360,000 kilowatts), Shunan-Shipai-Yushan power 2.71 million kilowatts (ultra-stable limit 300,000 kilowatts). Visible, TCPST can control Meili-Mudu run in the stability limit, but Shunan-Shipai-Yushan channel without control remains ultra-stable limit load.

After installation of TCPST, calculated, in the south of Suzhou (Mudu, Wujiang and Chefang) area limit load 800,000 kilowatts, the power flow of line and southern Jiangsu section can be controlled within stable limits. Therefore, compared to not install TCPST, after Jinsu UHVDC bipolar blocking Sunan region can be less shed load 1.1 million kilowatts.

**CONCLUSION**

TCPST string into the circuit by changing the line voltage compensation voltage amplitude or phase angle, in order to adjust the power flow, with improved interconnection power exchange, optimize network power control, the ability to enhance the transmission channel and suppress power disturbances and other functions. Therefore, this article build 3n hierarchical switching type TCPST based on BPA, designed series and shunt side parameters, established a steady simulation model to study the effect of regulation, the results show:

1) TCPST is able to transfer a wide range of power flow, enables flexible control of the power flow, especially in the important section, it can improve circulation gateways, uneven flow distribution and other issues;

2) Install TCPST near UHVDC area, can improve key channel power flow near placement, and improve the ability into direct in small DC load mode and to solve problems sending out in large DC load mode; in addition, by coordinating with security control measures, can reduce the load shedding after bipolar blocking.

In addition, the TCPST project overall cost is relatively low, but cannot achieve reactive power decoupling in the control system, so the system needs sufficient reactive support, the grid voltage stability issues with accessing of TCPST remain to be study.

**REFERENCES**