Separate Poles Mode for Large-Capacity HVDC System

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Abstract. This paper proposes a novel connection mode, separate poles mode (SPM), for large-capacity HVDC systems. The proposed mode focuses on the core issues of HVDC connection in interconnected power grids and principally aims at increasing effective electric distance between poles, which helps to mitigate the interaction problems between AC system and DC system. Receiving end of bipolar HVDC has been divided into different inverter stations under the mode, and thus significantly alleviates difficulties in power transmission and consumption of receiving-end AC grids. By investigating the changes of multi-feed short-circuit ratio (MISCR), finding that HVDC with SPM shows critical impacts upon itself and other HVDC systems with conventional connection mode, which demonstrates that SPM can make balance between MISCR increase and short-circuit current limit.

1. Introduction

HVDC connection is related to entire process of power system planning, design and operation. Especially large-capacity HVDC connection will be limited to manifolds with increment of HVDC projects and capacities. First of all, receiving AC system should be able to distribute HVDC power to each load center reasonably. Secondly, receiving AC system should support HVDC commutation sufficiently to meet the indices of SCR [1]-[4]. Furthermore, interactions between AC and DC will become more complex, and AC faults may cause multi-circuit HVDCs commutation failure simultaneously or successively in interconnected power grids, that will give danger to secure and stable operation of grids. HVDC connection is becoming an important issue which need to be properly investigated.

Optimal selections of HVDC terminal location and changes of connection modes will help large-capacity HVDC to connect into power system [5]-[9]. Considering the safety, stability and economy requirements, Qinyong Z and Kang W design a correlative evaluation system to evaluate influences of HVDC conventional connection by the indices of MISCR[5]-[6]. But these papers make no differences between positive and negative terminals. There is a UHVDC hierarchical connection mode proposed in [7]-[8], which proves that the mode is helpful to increase the voltage support capability of multi-infeed HVDC system. But the paper pays no attention to influence of the mode over other HVDCs in power systems. Multi-terminal connection mode of large-capacity HVDC systems has been studied in [9], which inclines to compare characteristics and fault responses of different modes, without theoretically verifying the validity of enhancing MISCR.

The objective of this paper is to propose a novel connection mode for large-capacity HVDC, and principally aims for increasing effective electric distance between poles. The main contribution is to demonstrate that SPM can lessen difficulties both in power transmission and consumption of
receiving-end AC grids. And it’s also proved that this mode will enhance the value of MISCR without raising short-circuit current of AC system.

The paper is structured as follows. Section 2 introduces structural characteristics of SPM. Section 3 analyzes impacts of SPM upon indices of MISCR. Section 4 compares the two modes while these applied on CSG planning data in section 5. The paper concludes in Section 6.

2. Structure of separate poles mode

In conventional connection mode, both positive and negative poles connect to the same commutation bus of receiving-end grids. But there are two inverter stations in SPM, while positive and negative poles are divided to connect to different commutation buses according to the load demand. Reactive power compensation and AC filter banks are configured in each bus. Structure of SPM is illustrated in figure 1.

This mode makes fully use of bipolar HVDC’s structure characteristics. Two poles of large-capacity HVDC are as directly independent receiving ends under this mode, so that the device quantities of bipolar control, pole layer control and the valve group control are equal to the conventional bipolar HVDC. And partial function of the bipolar control layer needs to be distributed to the pole control layer, because of reactive power compensation and AC filter banks configured by each pole. So the control technology of SPM is liable to come true.

3. Voltage support capability analysis under SPM

The index of MISCR takes interaction of each DC system into consideration, and accurately reflects AC system voltage supporting ability [10]-[11]. This paper selects this index to evaluate the variation of the voltage support capability under separate poles mode.
3.1. MISCR calculation under conventional connection mode

![Figure 2. Equivalent multi-infeed HVDC model](image1)

![Figure 3. Equivalent multi-infeed HVDC model with DC i’s using SPM](image2)

In view of the system shown in figure 2, there are [12]:

\[
\text{MISCR}_i = 1/\left(\left|Z_{eqi}\right|*P_{di} + \left|Z_{eqj}\right|*P_{dj}\right) 
\]

\[
\text{MISCR}_j = 1/\left(\left|Z_{eqj}\right|*P_{dj} + \left|Z_{eqi}\right|*P_{di}\right) 
\]

MISCR, (MISCR, j) is the value of MISCR for the \(i^{th}\) \((j^{th})\) DC system. \(P_{di}(P_{dj})\) is the rated power for the \(i^{th}\) \((j^{th})\) DC system. \(Z_{eqi}(Z_{eqj})\) is the \(i^{th}\), \(i^{th}\) \((j^{th}, j^{th})\) element in equivalent nodal impedance matrix. \(Z_{eqij}(Z_{eqji})\) is the \(i^{th}\), \(j^{th}\) \((j^{th}, i^{th})\) element in the equivalent nodal impedance matrix.

3.2. MISCR calculation under SPM

Let the large-capacity DC i’s system adopt SPM in the model shown in figure 2, that is, to keep the DC i’s pole placement unchanged, and to make the other pole connect to bus \(i'\), as figure 3 shows.

The system shown in figure 3, there are:

\[
\text{MISCR}_i' = 1/\left(\left|Z_{eqi}\right|*P_{di} / 2 + \left|Z_{eqj}\right|*P_{dj} / 2 + \left|Z_{eqi}\right|*P_{di}\right) 
\]

\[
\text{MISCR}_j' = 1/\left(\left|Z_{eqj}\right|*P_{dj} / 2 + \left|Z_{eqi}\right|*P_{di} / 2\right) 
\]

\[
\text{MISCR}_i'/\text{MISCR}_j' \text{ is the value of MISCR for the } i^{th}\ \(j^{th}\) \text{ DC system, } Z_{eqij}'/Z_{eqji}' \text{ is the } i^{th}\ \(i^{th}\) \((j^{th}, j^{th})\) \text{ element in the equivalent nodal impedance matrix.}
\]

From formula (1) \((4)\), we have:

\[
K_{Mi} = \frac{\text{MISCR}_i'}{\text{MISCR}_j'} = 1 + \frac{\left|Z_{eqi}\right| - \left|Z_{eqi}'\right|}{\left|Z_{eqi}\right| + \left|Z_{eqi}'\right| + 2\left|Z_{eqi}\right|*P_{di} / P_{dj}} 
\]

\[
K_{Mj} = \frac{\text{MISCR}_j'}{\text{MISCR}_j'} = 1 + \frac{\left|Z_{eqj}\right| - \left|Z_{eqj}'\right|}{\left|Z_{eqj}\right| + \left|Z_{eqj}'\right| + 2\left|Z_{eqj}\right|*P_{dj} / P_{di}} 
\]

\(K_{Mi}\) is the ratio of HVDC i’s MISCR in two kinds of connection mode. \(K_{Mj}\) is the ratio of HVDC j’s MISCR in two kinds of connection mode.

According to formula (5)-(6), the variation of DC i’s MISCR is related directly to the value of \(Z_{eqij}'/Z_{eqji}'\). The same as HVDC j.
3.3. MISCR Variation Analysis

From formula (1) to (4), it can be figured that changes of connection mode will have influence on each DC’s MISCR. This section will calculate variation of MISCR when DC i’s system connects to AC system by SPM.

3.3.1. MISCR variation of DC i’s system. According to the system showed in Figure 3, node admittance matrix Y can be written as:

$$Y = \begin{bmatrix}
\frac{1}{Z_{v'}} + \frac{1}{Z_{v'i}} + \frac{1}{Z_{v'i'}} & -\frac{1}{Z_{v'i}} & -\frac{1}{Z_{v'i'}} \\
-\frac{1}{Z_{v'i}} & \frac{1}{Z_{v'i}} + \frac{1}{Z_{v'i'}} & -\frac{1}{Z_{v'i'}} \\
-\frac{1}{Z_{v'i'}} & -\frac{1}{Z_{v'i'}} & \frac{1}{Z_{v'i'}} + \frac{1}{Z_{v'i'}}
\end{bmatrix}$$

Then, further obtain node impedance matrix Z by calculating the matrix inversion of Y. The value of $Z_{eqii}$ and $Z_{eqii'}$ can be obtained as follows:

$$Z_{eqii} = \frac{Z_{v'i}Z_{v'i'}}{\Delta} \left[ Z_{v'i}(Z_{v'i} + Z_{v'i'} + Z_{v'i}Z_{v'i'}) \right] + Z_{v'i}Z_{v'i'} \left[ Z_{v'i}(Z_{v'i} + Z_{v'i'} + Z_{v'i}Z_{v'i'}) \right]$$

$$Z_{eqii'} = \frac{Z_{v'i}Z_{v'i'}}{\Delta} \left[ Z_{v'i'}(Z_{v'i} + Z_{v'i'} + Z_{v'i'}Z_{v'i'}) \right] + Z_{v'i}Z_{v'i'} \left[ Z_{v'i'}(Z_{v'i} + Z_{v'i'} + Z_{v'i'}Z_{v'i'}) \right]$$

There, $\Delta$ is determinant of Y, from comparison of equation (8) and (9), we can see:

$$K_i = \frac{Z_{eqii}}{Z_{eqii'}} = 1 + \frac{Z_{v'i}(Z_{v'i} + Z_{v'i'} + Z_{v'i}Z_{v'i'})}{Z_{v'i'}(Z_{v'i} + Z_{v'i'} + Z_{v'i'}Z_{v'i'})} > 1$$

That means $Z_{eqii} > Z_{eqii'}$, according to formula (5):

$$\text{MISCR}_i > \text{MISCR}_i'$$

Compared with conventional HVDC connection mode, HVDC i’s MISCR has been improved, which means that the voltage support capability for HVDC i’s system get better.

3.3.2. MISCR variation of HVDC j’s system. Similarly, the value of $Z_{eqjj}$ and $Z_{eqjj'}$ are as follows.

$$Z_{eqjj} = \frac{Z_{v'i}Z_{v'i'}}{\Delta} \left[ Z_{v'i}(Z_{v'i} + Z_{v'i'} + Z_{v'i}Z_{v'i'}) \right] + Z_{v'i}Z_{v'i'} \left[ Z_{v'i}(Z_{v'i} + Z_{v'i'} + Z_{v'i'}Z_{v'i'}) \right]$$

$$Z_{eqjj'} = \frac{Z_{v'i}Z_{v'i'}}{\Delta} \left[ Z_{v'i'}(Z_{v'i} + Z_{v'i'} + Z_{v'i'}Z_{v'i'}) \right] + Z_{v'i}Z_{v'i'} \left[ Z_{v'i'}(Z_{v'i} + Z_{v'i'} + Z_{v'i'}Z_{v'i'}) \right]$$

From comparison of formula (12) and (13), we have:

$$K_j = \frac{Z_{eqjj}}{Z_{eqjj'}} = 1 + \frac{Z_{v'i}(Z_{v'i} - Z_{v'i'})}{Z_{v'i'} + Z_{v'i'}Z_{v'i'}}$$

If:

$$Z_{v'i}Z_{v'i'} > Z_{v'i'}Z_{v'i}$$

Then $K_j > 1$, $Z_{eqjj} > Z_{eqjj'}$, according to formula (6)

$$\text{MISCR}_j > \text{MISCR}_j'$$
So if DC i’s system using SPM and its’ placement selection suitably, the value of DC j’s MISCR will bigger than that using conventional connection mode.

Therefore, equation (15) can be used to limit placement selection of large-capability HVDC with SPM, which will increase the value of every HVDC’s MISCR, so as to integrally enhance AC system voltage support capability for DC system.

In addition, HVDC connection mode altering will not result directly in changes of short circuit capacity of AC system. If the value of MISCR is too little to become the “short-board” of system in aspects of safe and stable operation, SPM will play a key role on making a balance between MISCR improvement and short capacity limit, while short circuit of placement area closes to circuit breaker interrupting capacity. It follows that SPM will strengthen receiving system voltage support capacity for HVDC, and avoid to increase the risk of short-circuit current over-limitation.

4. Comparison between SPM and convention connection mode

4.1. Power dissolved capacity of AC system

It is difficult to completely consume active power delivered by large-capability HVDC under conventional connection mode. Converter station usually adopts “multi-contact” ways to transmit quantities of power to load nodes. This requires receiving AC system possess good capacity of power transmission and consumption.

Large-capacity HVDC with SPM takes advantage of HVDC power transmission and flexible controllability, and delivers active power directly to each load center. This will be beneficial to reduce difficulty of power consumption for receiving AC system, and achieve a reasonable load distribution, decrease network loss and enhance available transmission capacity of AC system at the same time.

4.2. Voltage support capacity

Conventional HVDC commutation depends on voltage support by AC system. Now MISCR is usually used to measure AC system voltage support capacity for multi-infeed HVDC systems. From formula of MISCR, it can be figured that AC system short-circuit capacity will enhance as HVDC transmission power increment. But in recent years, short-circuit current exceeding increasingly threat system safe and stability operation. Contradiction between short-circuit current restrictions and MISCR improvement get more obvious.

Large-capacity HVDC with SPM increases electrical distance between poles, and has advantages in improving each DC’s MISCR proved in section 3, which is help to enhance voltage support capability without causing a change in short-circuit current. In addition, combined with districting operation, it will reduce interaction between DC and AC system, weaken influences of faults on HVDC receiving ends, and has a great effect on promoting stability and security of power system operation.

5. Test case for SPM

This paper uses planning data of China Southern Power Grid in 2020 as the example. Guangdong power grid realizes the goal of partitioning by three back-to-back HVDC projects. And the Dianxibei HVDC terminal locates in 500 kV Conglin bus, and its rated power is 5000MW, which has been designed to different connection modes in the case. The area wiring diagram round it in 500 kV voltage grade is showed in figure 4.
Two connection modes are compared in the simulation. Conventional connection mode is called mode1, that Dianxibei HVDC receiving poles all connection to CL 500kV bus. The SPM is called mode 2, in which positive pole of Dianxibei HVDC receiving end connects to ZJ 500 kV bus while the negative pole connects to CL 500 kV bus.

5.1. **Comparison of Power Flow**
As shown in table 1, the value of active power from CL to ZJ is 2420MW in mode 1 while there is only 251MW in mode 2. And the other lines power flow changes are not obvious. There are nearly 2200MW active power transmitted by positive pole, reducing the delivery pressure of AC lines.

| Lines | Mode 1(MW, MVar) | Mode 2(MW, MVar) |
|-------|-----------------|-----------------|
| CL-PC | 2*(800.2-j119.8) | 2*(702.2-j71.9) |
| SZ-PC | 2*(138.9-j33.9)  | 2*(149.1-j61.6) |
| BA-PC | 2*(158.2-j23.8)  | 2*(245.8-j7.6)  |
| BA-ZOJ| 2*(11.9+j56.5)   | 2*(2.6+j84.2)   |
| CL-ZJ | 2*(1210-j62.4)   | 2*(125.5+j33.6) |
| ZJ-XD | 2*(582.6-j77.5)  | 2*(686.9-j69.1) |

5.2. **Comparison of MISCR**
Obviously, the value of MISCR in mode 2 is larger than it in mode 1. That means voltage support capacity of AC system enhanced by adopting SPM without increasing the risk of short-circuit current over-limitation, as shown in table 2.

| HVDC  | Mode1 | Mode2 |
|-------|-------|-------|
| Positive pole | 3.06174 | 3.05127 |
| Negative pole | 3.06601 | 3.10902 |

5.3. **Comparison of Critical Clear Time**
As shown in table 3, critical clear time plays an important role in assessing AC system transient stability. The value of it in mode 2 is bigger. Therefore, using SPM will also be beneficial to strengthen the transient stability of power systems.

| Modes | Fault site | Critical clear time (cycle) |
|-------|------------|----------------------------|
| Mode1 | ZJ         | 7. 66                      |
| Mode2 | ZJ         | 8. 54                      |
5.4. Voltage Transient Characteristics

A three-phase fault firstly occurs at the head of no.1 line of ZJ to XD at 1s. Then switches of the two buses of the fault line are open after 0.1s, but the switch of one phase rejects action. At 1.45s, backup protection cut off no.1 loop of ZJ-XD and no.1 loop of CL-ZJ. The voltage curves of bus CL and bus ZJ under two modes as shown in figure 5-6.

![Figure 5. The voltage curves of CL bus under complex faults](image1)

![Figure 6. The voltage curves of ZJ bus under complex faults](image2)

After the failure, AC system has been unable to maintain voltage stability when Dianxibeih HVDC connects to receiving end by conventional connection mode. And with SPM, the voltage of nodes has resumed to normal and the recovery rate of nodes’ voltage has improved, which can be seen that the SPM will contribute to nodes’ voltage restoration in a way.

6. Conclusion and Outlook

Control technology of SPM is similarly to conventional connection mode, so it’s prone to implement. In addition, large-capacity HVDC receiving poles has been divided to different ends connected directly to each load center, which is beneficial to power transmission and distribution. That will reduce the difficulty of power consuming for AC grids with large-capacity HVDC.

Furthermore, large-capacity HVDC with SPM increases effective electrical distance between positive and negative pole. That makes a contribution to improving integrally voltage support capability of multi-infeed HVDC system, and take a good balance between short-current restriction and MISCR improvement. But the function of MISCR improvement is related to reasonable placement selection under SPM, so future work will concentrate on it.

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