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Research on Short-Circuit Control in the Receiving-End Power System with Multi-Infeed DC Transmission

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Abstract. The short-circuit current level is an important index to evaluate power system strength. With increasing transmission capacity between different zonal power systems, the receiving-end grid is gradually confronting with the network structure with multi-infeed DC transmission.The status quo requires better control on short-circuit capacity so as to assure the safe and stable operation of the DC-AC hybrid power system. In this paper, the interaction among short-circuit current, the transmission capacity of DC tie-line, and the voltage support is studied. Moreover, on the basis of the average difference between short circuit ratio(SCR) and multi-infeed short circuit ratio(MISCR), a novel method for short-circuit current control is proposed. Synthesized with the latest ultra-high voltage network planning in Eastern China Grid, the specification for short-circuit control of converter station is also put forward, which can address the constrains of multiple DC interconnections in Eastern China Grid. The research work presented in this paper can afford the guidance information to future planning in terms of the location decision for converter stations in the receiving-end system with multiple DC interconnections.

Introduction

The short-circuit current level plays a pivot role in the process of equipment selection. From the conventional perspective, large short-circuit current requires that the involved devices should possess high mechanical and thermal tolerance, in conjunction with the large conduct size. In order to assure the dependable fault component clearance after short-circuit, the circuit breaker is supposed to possess sufficient breaking capacity to swith off the short-circuit loop. Since the device cost rises up with its breaking capacity, it is necessary to limit the short-circuit current in power system operation. However, recent research indicates that the short-circuit current level is also a vital index to praise the strength of an AC system. Generally speaking, high short-circuit current usually implies the large-scale interconnections of synchronous generators, and synchronous generators are essential sources of reactive power and voltage support. During the post-fault process, the reactive power and voltage support is precious and crucial to dampen the power oscillation and voltage vibration. To be specific, the voltage support can boost converter station's ability is to resist disturbance due to the fact that DC transmission is vulnerable to voltage perturbation. Therefore, short-circuit current should be properly controlled to both satisfy the requirements from system strength and rating breaking capacity of the circuit breaker.

With the sustainable development and economic advancement in China, the scale of power load and supply capacity is continuously augmenting and the network structure is constantly enhancing, which begets unduly short-circuit current and deteriorates the security risk of the main load center in power grid. Measures have been taken to maintain that the growing short-circuit current level can still be addressed by circuit breaker, such as opening or reconnecting circuit lines, installing short-circuit current limiter, etc. In addition, the energy resources are mostly located in the areas that are distant from load centers, and consequently the directions of power transmission tend to be "from West to East, from North to South". This pattern of transmission directions will maintain unchanged with a long period due to the inherent distance between the resource locations and the affluent zones in China, thereby urging the power grid to utilize the DC transmission with large capacity and distance.

In recent years, the latest power system planning drives up the implementation of the West to East power transmission strategy, and the trans-regional capacity increases constantly. The structure of receiving-end system gradually includes multiple interconnections of High-Voltage Direct Current (HVDC) transmission. Taking the Eastern China Grid as an example, seven HVDC transmission lines have already been undergo their operations, and five more HVDC transmission lines will be constructed by 2020. The Eastern China Grid will be fed by 12 HVDC transmission lines, and it will become the most intricate AC-DC hybrid system in the world.

Studies reveal that the voltage stability with the interaction between AC and DC system is the most noteworthy issue when the stability of a system with Multi-infeed DC transmissions is under research [1]. When reactive power disturbances occur, bus voltage fluctuation amplitude is inversely proportional to the short-circuit capacity. Short-circuit capacity level can substantially influence the system security and stability hence it needs to be reasonably controlled. On one hand, short-circuit current should satisfy the economic constraints. On the other hand, it should afford sufficient voltage support for the sake of security and stability. Currently, most research works on the short-circuit current are concerned with upper limitation, which should be controlled to satisfy the rating breaking capacity of the circuit breaker and the requirements of economic operation. For example, short-circuit current is supposed to be lower than 63kA in the 500kV power grid.In the meanwhile, the existing studies hardly involve the lower bound of the short-circuit current in AC-DC power system.

The structure of this paper is organized as follows: initially, this paper proposes a reasonable range of short-circuit current level with both upper and lower limitations. The range is via the consideration that how short-circuit current affects system security and stability from two aspects, namely, tie-line transmission capacity and voltage stability. Then, based on short circuit ratio (SCR) [2,3,4,5,6, 7,8,9,10,11,12] and multi-infeed short circuit ratio (MISCR) [13,14], the control requirement of short-circuit current level is put forward. The final part illustrates the proposed specifications with the example of East China Grid. This study on short-circuit current also provides the reference filter for converter station location candidates.

Impact of Short-Circuit Current on Power System Security and Stability

This section briefly presents how short-circuit current affects system security and stability from two aspects, namely, tie-line transmission capacity and voltage stability, then put forward the control principles of short-circuit current level.

The basic relation among short-circuit capacity, voltage and short-circuit current is shown as follows:

$$S_k = \sqrt{3}\, U_N\, I_k'' \tag{1}$$

where S_k is the short-circuit capacity of Bus k in a power system, U_N is the rating voltage level of Bus k, I_k'' is the short-circuit current of Bus k. So with a specific voltage level, the short-circuit current is directly proportional to the short-circuit capacity at the same bus.

Impact of Short-Circuit Current on the Tie-Line Transmission Capacity. In the practical calculation of short-circuit current, the exterior system can be equalized as a voltage source with internal impedance via Thevenin Equivalence Method. If all parameters are calculated in per unit system, the voltage source is approximate 1.0, and the short-circuit current contributed by the equivalent system is the reciprocal of equivalent impedance.

The simplified model of a typical single generator-equivalent system is illustrated in Fig. 1. In this example, the generator is connected to the 500kV bus of equivalent system through a step-up transformer (omitted in Fig.1) and 299 meters of paralleled LGJ-630×4 lines.

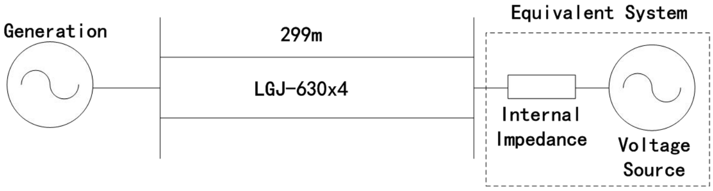

Figure. 1 Illustration of Single Generator-Equivalent System

The static stability limit of the system in Fig.1 is inversely proportional to the addictive impedance of generation, transformer, transmission lines and equivalent system. While the impedance of the equivalent system increases, the short-circuit current contributes by the equivalent system decreases. Thus the system tends to be more stable with greater short-circuit capacity in terms of static stability. Considering that the static stability limit tends to surpass transient stability limitation in real power system. Single-phase grounded fault is simulated to validate the transient stability limit and to analyze the relation between transient stability limit and short-circuit capacity.

The simulation result is demonstrated in Fig. 2. It is apparent that the transient stability limit is inversely correlated to the equivalent impedance. Therefore, the impact trend is similar with static stability. Therefore, the decrease in short-circuit current gives rise to the decrease of tie-line's transient stability limit.

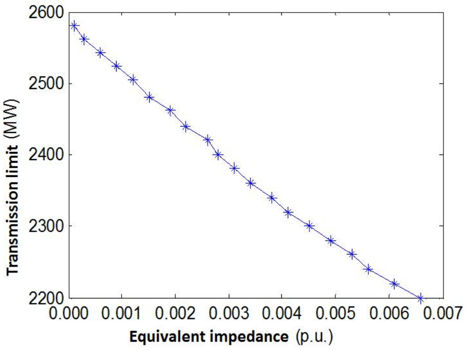

Figure. 2 Influence of Short-Circuit Capacity on Transmission Capacity

Impact of Short-Circuit Current on Voltage Support Capacity. If reactive power disturbance occurs, the voltage fluctuation amplitude is inversely proportional to the short-circuit capacity:

$$\Delta U_k = \frac{\Delta Q_k}{S_k} \tag{2}$$

where ΔU_k is the voltage deviation of Bus k with disturbance, ΔQ_k is the corresponding change of reactive power injection in Bus k.

It is apparent from (2) that the increase of short-circuit current causes a decrease of voltage change when the reactive power change is constant, as well as relieved voltage stability.

Short-Circuit Control Principles. The above analysis asserts that higher short-circuit current level comes with better operation stability and stronger capability to resist disturbances in power system. However, short-circuit current is strictly restrained by the breaking capacity of circuit breaker. Short circuit current control levels for each voltage rank of main transmission and distribution network in China are listed in Tab. 1.

Tab. 1 Objectives of Short-Circuit Current Control for Each Voltage Level in a Practical Grid

Voltage Level（kV）	1000	750	500	330	220	110
Control Target（kA）	63	63	63	63	50	40

Generally speaking, Short-circuit current level should adapt to the power transmission and the transformation equipment manufacturing level as well as power system operation and control level. Coordinating technique and economy, short-circuit current is supposed to be controlled within a reasonable range. A certain short-circuit current level is suggested to maintain as safety reserves of power grid within the rating breaking capacity of circuit breaker. If the short-circuit current level is rather low, measures should be taken to gradually raise up the short-circuit current in order to promote the ability to resist disturbances.

Short-Circuit Current Control Level in AC-DC Hybrid Grid

The AC-DC interaction largely depends on the ratio of AC system short-circuit capacity to the infeed DC system, namely SCR. SCR is often utilized to evaluate the relative strength relation between AC system and DC system. For the multi-infeed HVDC case, the evaluation result often tends to be optimistic if simply using SCR. MISCR is more suitable to evaluate the relative strength relation between AC system and DC system in multi-infeed HVDC system.

Short-Circuit Current Control Level Based on SCR. Fig. 3 is beneficial to illustrate the definition of SCR. It is AC-DC hybrid system with simplification of the AC system as an ideal voltage source and equivalent impedance in series based on Thevenin equivalence.

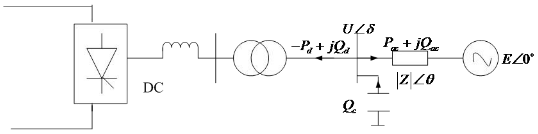

Fig. 3 Simplified Model of Single-Infeed HVDC system

SCR is defined as the ratio of AC system short-circuit capacity to the infeed DC system, which is denoted as K_{SCR}:

$$K_{SCR} = \frac{S_{ac}}{P_s} = \frac{\sqrt{3}\, I_{ac} U_a}{P_d} \tag{3}$$

where S_{ac} is the short-circuit capacity of DC landing commutation bus, P_d is the DC capacity, I_{ac} and U_a are the short-circuit current and operation voltage of DC landing commutation bus, respectively.

Based on the DC operation experience domestic and abroad, the classification of system strength according to SCR is given as shown below (via [15]):

Extremely weak system: K_{SCR}<2;

Weak system: 2<K_{SCR}<3;

Strong system: K_{SCR}>3.

Therefore, the specific infeed scheme is ignored in the initial selection of DC-infeed location, and the selection only treats the grid that receives DC power as a single power injection point via a short line. The final selection is supposed to meet the standard of strong system, i.e., K_{SCR}>3.

It can be seen from (3) that the requirements of short-circuit current vary from the differences in DC capacity and infeed voltage rank. The short-circuit current range of strong system with SCR above 3.0 can be deducted from (3). The possible DC receiving location is preliminary sifted out based on the analyzed result. Now long distance and large capacity HVDC is usually feed in the ultra-high voltage and above. Therefore, this research focuses on choosing HVDC landing location in the 500kV and 1000kV power grid. Tab. 2 presents the minimum of the short-circuit current for HVDC infeed location under different HVDC capacities and voltage levels.

From Tab.2 and Fig.4, the required short-circuit current is positively associated with the HVDC capacity but negatively correlated to AC voltage level of the DC-infeed point. With the current HVDC maximum capacity as 10000MW and the minimum voltage level as 500kV, short-circuit current of a strong system is above 33kA. Taking the 500kV breaking capacity into consideration, the short-circuit current is supposed to be controlled in the range of 33kA~63kA. It is simple to achieve a mature power grid except some specific remote areas. Therefore, from the viewpoint of SCR, most power grids can meet the basic requirements. A vast number of locations for converter stations can be found even with the infeed-HVDC maximum capacity 10000MW.

Tab. 2 The Required Minimum Short-Circuit Current with Different Voltage Rank and DC Capacity (Single-Infeed DC Grid)

Voltage Level（kV） / HVDC capacity（MW）	500	1000
1200	4.0	2.0
3000	9.9	4.9
4000	13.2	6.6
8000	26.4	13.2
10000	33.0	16.5

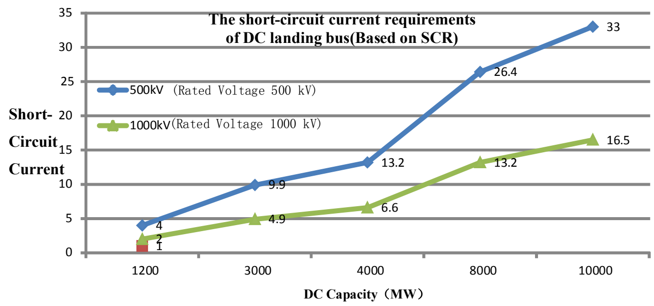

Figure. 4 Requirements of Short-Circuit Current for Converter Station in Receiving-End System (single-infeed SCR)

Definition of MISCR. Through Multi-Port Thevenin Equivalent Method (via [16,17]), multi-infeed DC system is simplified as shown in Fig. 5.

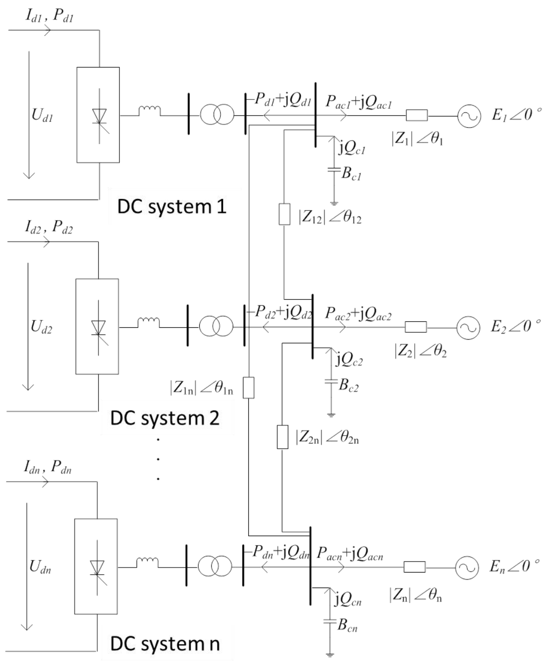

Fig. 5 Simplified Model of Muti-Infeed HVDC System

Referring to the definition of traditional SCR, MISCR is defined as the ratio of AC short-circuit capacity to equivalent DC capacity considering the multi-infeed DC interaction.

$$K_{MISC_i} = \frac{S_{ac_i}}{P_{dep_i}} = \frac{S_{ac_i}}{P_{d_i} + \sum_{j=1,\, j\neq i}^{n} \left| Z_{eq_{ij}} / Z_{eq_{ii}} \right| P_{d_j}} \tag{4}$$

where i and j are the number of commutation buses, K_{MISC_i} is the MISCR at the commutation bus of the i-th DC system, $Z_{eq_{ii}}$ is the self-impedance of the i-th DC system in the equivalent impedance matrix, $Z_{eq_{ij}}$ is the mutual impedance between the i-th and j-th DC system in the equivalent impedance matrix, P_{d_i} and P_{d_j} are the rating capacity of the i-th and j-th DC system.

From Equation (4), it is manifest that MISCR is smaller than SCR in multi-infeed DC system because of the multi-infeed DC interaction. The variation between MISCR and SCR depend on the relative value of P_{d_i} and $\sum_{j=1, j=i}^{n} \left| Z_{eq_{ij}} / Z_{eq_{ii}} \right| P_{d_j}$.

Control of Short-Circuit Current Control Level Based on Mean Difference Between MISCR and SCR. As MISCR represents the multi-DC interaction, it only exists in multi-infeed DC system. From (3) and (4), MISCR is smaller than SCR especially in the intensive DC-infeed areas. Therefore, there may be large error if the short-circuit current requirement is put forward directly based on the SCR in multi-infeed DC system.

For the areas where the DC-infeed scales reach a certain level, especially the intensive DC-infeed areas, the mean difference between SCR and MISCR is considered relatively conservative and reliable. Referring to the classification of system strength according to SCR, a method to assess the multi-infeed DC system is put forward.

Here are the steps to obtain the short-circuit current control level based on the mean difference between SCR and MISCR:

Step1: Calculate the SCR via (3);

Step2: Calculate the MISCR via (4);

Step3: Calculate the mean value of the difference between SCR and MISCR in the area with intensive DC infeed;

Step4: Treat the sum of the mean value from step (3) and 3.0 as the new required SCR' ;

Step5: Put SCR' to (3) to calculate the minimum short circuit current value that assures the strong receiving system.

Case Study in a Practical and Typical Multi-Infeed HVDC System

The Relationship Between SCR and MISCR of Eastern China Grid. According to the latest planning, 12 DC transmission projects will be interconnected with Eastern China Grid by 2020.

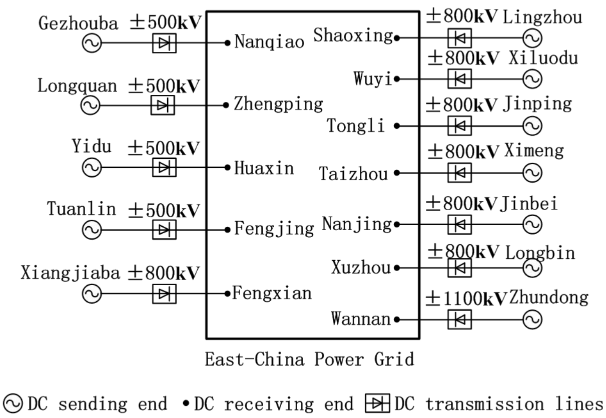

Fig. 6 Illustration of Eastern China Grid with Multiple DC Interconnections

As shown in Fig. 6, UHVDC hierarchical connection mode is applied in Taizhou, Wannan and Xuzhou Converter Stations. One pole is connected to the 1000kV AC layer and another pole is connected to the 500kV AC layer. In this case, the single polar capacity is considered in the SCR calculation. The required minimum short circuit current with different voltage rank and DC capacity is shown in Tab. 3.

Tab. 3 The Required Minimum Short-Circuit Current with Different Voltage Rank and DC Capacity

No.	DC-infeed Site	Rating Capacity （MW）	SCR	MISCR	Difference
1	Tongli	7200	5.1	3.6	1.6
2	Nanjing	8000	6.4	4.1	2.3
3	Wuyi	8000	6.1	4.4	1.8
4	Zhengping	3000	13.1	6.2	6.9
5	Taizhou	10000	8.9/7.7	5.4/4.4	3.5/3.3
6	Shaoxing	8000	6.9	4.9	2.1
7	Fengxian	6400	8.2	4.4	3.8
8	Nanqiao	1200	41.5	4.4	37.2
9	Fengjing	3000	9.3	3.4	5.9
10	Huaxin	3000	8.1	3.2	4.9
11	Wannan	12000	6.8/5.3	5.4/5.0	1.4/0.3
12	Xuzhou	10000	8.9/8.	7.7/4.7	1.2/3.6

Conclusions from the presented results in Tab. 3 are as below:

(1) Nanqiao has the greatest difference between SCR and MISCR among all the ±500kV DC, this is due to the fact that the rating capacity of Nanqiao is the lowest and the multi-infeed DC interaction is most substantial.

(2) MISCR of Wannan is the smallest, it is due to the fact that Wannan is far from the other DCs in both geographical distance and electrical distance. Little effect is put on Wannan DC by the other DCs. Therefore it can be regarded as the single DC system for Wannan DC.

(3) The maximum difference between SCR and MISCR of a±500kV DC is as large as 37.15 and the mean difference is 13.7. The maximum difference between SCR and MISCR of a±1000kV DC is as large as 3.78 and the mean difference value is 2.10. Some ±500kV DCs possess relatively low capacity, thereby intensifying multi-infeed DC interaction, and raising the mean level of SCR and MISCR.

(4) On the assumption that all DC systems possess the uniform capacity, the MISCR of 1000kV layer is relatively higher than 500kV layer.

Required Short-Circuit Current Control Level Based on MISCR. If the classification of power system strength based on SCR is carried on in multi-infeed DC system, the required short-circuit current level grows up sharply. For example, the SCR in Jiangsu power grid is about 2.10 higher than MISCR, while if the MISCR is also required to reach 3.0 and above, the SCR turns up above 5.10. The corresponding short-circuit current has to be controlled in the range of 44.89/56.09kA~63kA assuming the DC capacity as 8000/10000 MW. The required minimum short circuit current with different voltage rank and DC capacity in multi-infeed DC grid is shown in Tab.4 and Fig.7.

Tab. 4 The required minimum short circuit current with different voltage rank and DC capacity(multi-infeed DC grid)

Voltage Level(kV) / DC capacity（MW）	500	1000
1200	6.7	3.4
3000	16.8	8.4
4000	22.4	11.2
8000	44.9	22.4
10000	56.1	28.0

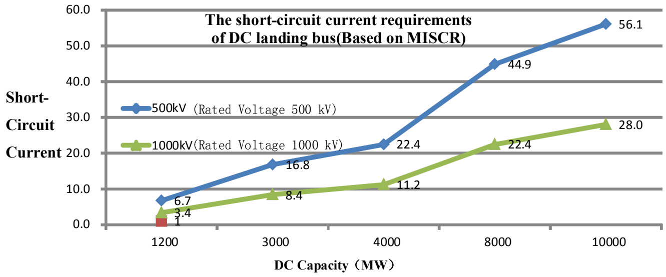

Fig. 7 DC Output Location's Requirements for Short-Circuit Current (Deducible MISCR)

Conclusions

In this paper, the relationship between short-circuit current and power network security and stability is studied. The minimum control requirements of different capacity DC HVDC accessed to different voltage levels for single DC system and multi-infeed DC system are proposed and fully analyzed. Taking into account of all these factors, the following conclusions can be obtained:

(1) The short-circuit current in the load center should not be minimized as much as possible, it is supposed to be maintained in a reasonable range to satisfy the backup support for stability and enough margin for the rated capacity of breakers.

(2) The control requirements of HVDC power converter bus short-circuit current and DC voltage level are related to capacity and access, which will increase with the growth of the DC capacity and decrease with the ascent of the access voltage;

(3) Judgment standards based on SCR can be utilized as a selection method of short-circuit current control standard for a single DC or multi-infeed DC with long relative distance in the DC/AC system. However, it will be rather low for the multi-infeed DC system. In this case, judgment standards based on MISCR should be utilized to the short-circuit current control.

(4) The proposed method can provide approximate estimation for DC substation selection in the power grid with fine precision, which can greatly reduce the workload. And it will provide some techniques for the planning and construction of power grid, which is convenient for engineering practice and application.

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