Redistribution of DC Power in Multi-terminal Flexible DC Transmission Systems

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***Abstract*—When there are faults in AC grid, one of the concerns is power distribution as well as system stable operation while AC grid in fixed DC voltage side goes wrong. The second point of concern is power distribution of other converter stations while certain converter station fails. Moreover, based on VSC-MTDC system balance control strategy with additional active power signal, power distribution and DC voltage control which are performed when DC voltage station fails are realized through introducing additional active power signal based on adjustable active capacity margin at fixed active power converter station so that stable operation in VSC-MTDC system can be enhanced during faults.**

Keywords-Multi-Terminal Flexibility; DC Transmission; Power Redistribution

I. INTRODUCTION

Multi-terminal flexible direct current transmission system (VSC-MTDC) that can realize multi-power supply and multi-drop power receiving has better economic benefits and flexibility than two-end flexible system, which is an important development direction for direct current transmission system. What's more, DC voltage stability and power coordinated control are the main objectives of the VSC-MTDC system, and focus in this paper mainly lies in which master-slave control, DC voltage deviation control and voltage drop control are adopted to coordinate and improve control strategies when system is in steady operation and power is changing. Mode switching control strategy under AC grid fault in DC voltage control terminal can ensure that when there are different types of faults in AC power grid of fixed DC voltage terminal, if receiving AC bus is single-phase grounded, absorbed power in faulty inverter will be reduced in VSC-HVDC transmission system. If system power redistribution is not considered, receiving power in non-fault side of receiving end will be basically unchanged, and output power of the first terminal with constant DC voltage control will be reduced to maintain basic stability of DC voltage. Therefore, after power redistribution control proposed in this paper is performed, the second terminal is single-phase grounded, and receiving power in the third terminal is increased from 200MW to 300MW. Besides it, power at the first end is unchanged. Moreover, after the third terminal is single-phase grounded, the absorption power at the second terminal is increased from 100 MW to 200 MW, and power output at the first terminal is reduced from steady 300 MW to 270 MW. Similarly, when single-phase grounding occurs in receiving end of AC grid, range of DC voltage variation in the system will be reduced after power redistribution[1-2].

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II. INTRODUCTION ON VSC-MTDC MODEL

Typical VSC-MTDC transmission system for electric field is shown in Figure 1.

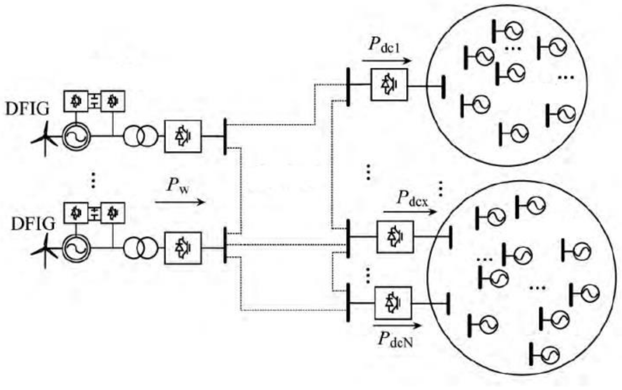

Figure 1. Typical VSC-MTDC Transmission System

Electric field group is composed of a plurality of offshore wind farms, and each electric field is provided with plenty of wind power generators for generating electricity. Moreover, total electric power Pw generated by electric field feeds wind power into M asynchronous AC grids through N receiving converter stations on the shore[3].

For the scenario where offshore wind farm under study is connected to AC grid, more reasonable control method is that all onshore receiving stations are involved in the power stability of DC grid. Therefore, as it can be seen in this paper, active-voltage (P-U) droop control is adopted in N-side converter stations so that the distribution of DC power among converter stations can be determined by droop curve, and P-U pendant controller in converter station i is shown in Figure 2.

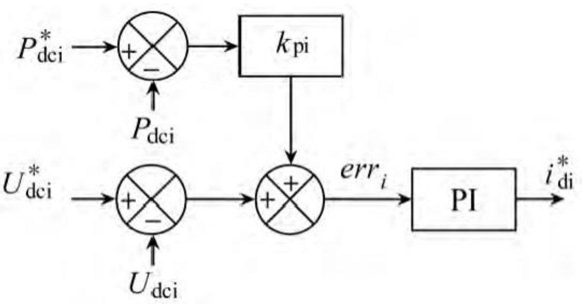

Figure 2. P-U Sag Controller in Converter Station *i*

In Fig. 2, subscript i represents the amount related to converter station i, erri is the input of PI control module, and kpi refers to the slope coefficient in droop control. Besides it, P*dci and U*dci are reference values of DC power and DC voltage set by converter station i, and Pdci and Udci are the measured values of DC power and DC voltage in VSC-MTDC system with offshore wind farm in Figure 1.

III. DC POWER REDISTRIBUTION STRATEGY WHEN CONVERTER STATION EXITS

There are two goals for redistribution. One is that control parameters of converter station after fault are re-adjusted to prevent power from being transferred to asynchronous AC grid through other converter stations so that influence range of transfer power can be reduced. The other is that the influence of power flow redistribution on frequency stability performance in receiving network where converter station x is located can be reduced. The redistribution strategy at this time is as follows.

A. *Sensitive Cluster Division of Converter Station*

For converter station i, the change in its active power will only have significant effect on angular velocity of the unit, which is close to its electrical distance, and the units are referred as sensitive fleet of converter station. Additionally, sensitivity coefficient is defined as power variation of angular velocity of generator j relative to converter station i, ie:

$$SI_{j,i} = \frac{\partial w_j}{\partial P_{dci}} \tag{1}$$

Usually, the maximum value in SI matrix is used as reference, that is, sensitivity coefficient has been set.

$$\mathrm{NSI}_{j,i} = \frac{\mathrm{SI}_{j,i}}{\max(\mathrm{SI})} \tag{2}$$

Sensitivity coefficient is obtained by calculating short-term unit speed change in the case where a small amount of power disturbance is introduced to converter station iwhen steady operation is performed in the system. Therefore, sensitivity coefficient is only related to the structure and unit characteristics in onshore AC system, which refers to offline calculation amount in this paper. In subsequent transient behavior, it can be selected from the table according to the structure of onshore AC system and the change of unit characteristics, and recalculated is not needed any more[4-5].

B. *Power Optimization Redistribution Aiming at Increasing Frequency Stability in AC System*

There is room for optimization in distribution scheme of consumption, and three converter stations x、y1、y2whose sensitive groups are set to SCx、SCy1andSCy2where SCx and SCy2have public sensitive units while SCx and SCy1 do not have common sensitive unit are included in receiving AC system. Moreover, after converter station x exits operation due to faults, sensitive cluster SCx corresponding to converter station x has a lack of priority induction power, which will cause the units in SCx to participate in active power adjustment and their speed will be slow. At this time, following two types of power transfer need to be considered. When transfer power is mainly consumed by converter station y1, increase ofPdcy1 mainly affects SCy1so that rotation speed of the unit in SCy1tends to increase. However, since increase in Pdcy1 has less impact on the units in SCx, this kind of allocation will lead to consequence that unit speed in SCy1 will be significantly faster than that in SCx, which will increase the relative power angle of units in two groups, especially the first pendulum[6].

When transfer power is mainly consumed by converter station y2, increase of Pdcy2 mainly affects SCy2so that rotation speed of the unit in SCy2tends to increase. Since SCy2 and SCx have common sensitive unit, tread increasing unit speed in SCy2 partially offsets the trend slowing speed of common unit inSCx. As a result, power angle variation of the unit in SCx is reduced, and the grid frequency is restored more stably. From the above analysis, the first criterion is obtained, that is, when transfer power is allocated, converter stations which have strong ability to adjust sensitive units in converter station x should be preferentially selected.

Design idea on power optimization redistribution is as follows. In receiving end system S, power △ Pdcy consumed by other converter stations y other than converter station x is an optimized object, and frequency fluctuation in receiving system S can be expressed by the weighted average of rotational speed fluctuations △ ω i in each unit. Besides it, weight coefficient is inertia constant Hi of the unit. What's more, when power redistribution is performed, angular velocity fluctuation of unit j in SCx can be assumed in a large-scale AC system where plenty of general units exist, which brings a large amount of calculation to subsequent optimization. Therefore, in order to simplify optimization process, only sensitive unit is considered, and non-sensitive unit element NSIj，i which is smaller than threshold NSIthr is set to zero[7]. ie:

$$\mathrm{NSI}^{*}_{\mathrm{j,i}} = \begin{cases} 0, (\mathrm{NSI}_{\mathrm{j,i}} < \mathrm{NSI}_{\mathrm{thr}}) \\ \mathrm{NSI}_{\mathrm{j,i}} (\mathrm{NSI}_{\mathrm{j,i}} \geq \mathrm{NSI}_{\mathrm{thr}}) \end{cases} \tag{3}$$

The first optimization idea is to set △ fs minimization to the goal of optimization, which achieves the stability of overall frequency in the grid, but does not take into account the fact that it is possible that as some of the local frequency fluctuations in unit are large, a large impact on frequency-sensitive load near the units will occur. Therefore, in order to consider the situation mentioned above, system frequency fluctuation factor vector can be defined as

$$I_f = [\Delta w_1, \Delta w_2, \cdots, \Delta w_i \cdots, \Delta w_M], i \in S \tag{4}$$

When power optimization is performed, the unit with the largest value in frequency fluctuation factor vector If from minimized system can be considered as well. As a result, considering the minimization of system frequency deviation △ fs and the minimization of infinite norm in system frequency fluctuation factor vector If, optimization can be expressed by the following equation, where c refers to the weight coefficient of combination optimization whose value is related to inertia distribution of the unit in system.

IV. CONCLUSION

Power redistribution control strategy for AC side bus fault in multi-terminal flexible DC transmission system is proposed in this paper, and it is judged whether the fault occurs according to receiving power change on receiving end. When power is less than the fixed value, active value of non-fault side voltage on receiving end will be changed to realize power redistribution without overload. Besides it, simulation model in three terminals flexible DC transmission system with active network on AC side is established with the help of PSCAD. In conclusion, redistribution of multi-terminal flexible DC power proposed in this paper enhances the stable operation capability of transmission system during faults.

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