Control of Multi-Terminal VSC-HVDC System to Integrate Large Offshore Wind Farms

Xiongguang Zhao, Qiang Song, Hong Rao, Xiaoqian Li, Xiaolin Li, and Wenhua Liu

Abstract—This paper presents operation and control strategies of multi-terminal HVDC transmission system (MTDC) using voltage source converters (VSCs) for integrating large offshore wind farms. The framework and operation principles of the proposed system are described and control strategies for coordinating various VSCs are proposed. DC voltage control based on the DC voltage-current (V-I) droop characteristic of grid side converters is implemented, to ensure stable system operation and flexible power dispatch between various onshore AC grids. To validate the performance of the proposed control strategies, a typical four terminal MTDC networks, which connecting two offshore wind farms with two onshore AC grids, is established in PSCAD/EMTEC. Simulation results under normal and abnormal operation conditions verify the satisfactory performance of the proposed control strategy and accuracy of the theoretical analysis.

Index Terms—Control, HVDC, multi-terminal, voltage source converter, wind farm.

I. INTRODUCTION

As wind power is a kind of environmental friendly energy and abundantly available in nature, the China government has set a target of developing 200GW wind farms by 2020 in order to deal with global warming and achieve a goal that 15% of power consumption is provided by renewable energy. Offshore wind farms will increase to 30GW according to the target and are developing rapidly in recent years. Integrating the offshore wind farms to the grid over a long distance is one of the main challenges facing researchers. Previous studies have indicated that high voltage DC (HVDC) transmission has a lot of advantages over traditional AC transmission, including fewer cables required, not affected by the cable charging current and flexibly controlled power flow [1], [2]. Compared with line commutated converter (LCC) HVDC, the VSC-HVDC shows many advantages [3]-[7]. These include avoiding commutation failure, the independent control of active and reactive power, no voltage polarity reversal required to reverse power, producing less harmonic, less filters required and continuous AC bus voltage regulation. Because of the above reasons, VSC-HVDC is considered as a promising solution to integrating large offshore wind farms into onshore AC grids and has attracted a lot of research [5]-[8].

In VSC-HVDC, VSC multi-terminal HVDC (VSC-MTDC)

transmission system, which consists of more than two converters connected through DC cables, can reduce the number of converters and improve the flexibility and reliability, when compared to numerous point to point HVDC systems. But the challenge is that the operation and control of VSC-MTDC is more complex. Various control strategies have been proposed for VSC-MTDC [9]-[11]. In [9], a voltage margin control method was proposed, in which each converter station in the system was given a marginally offset DC voltage reference. At any time, only one converter is used to control the DC voltage in this method. Reference [10] designed a control method based on the voltage-power characteristic of the converters for a MTDC system without fast communication. In [11], a current matching control was used to control the DC current and power sharing ratio among the AC grids. This kind of control depended on the communication equipment to transmit current information. The deficiency of the above control methods is that they can't allow multiple converters to control the DC voltage and change the power sharing ratio between the receiving AC grids without communications simultaneously.

This paper proposes a control method, which allows multiple converters to control the DC voltage and can dispatch the power between the receiving AC grids of MTDC system at a pre-defined ratio without the use of communications between terminals. The control method combines the voltage control with the V-I characteristic of grid side VSCs (GSVSCs). The paper is organized as follows. Section II introduces the system configuration and describes the main control strategies. Simulation results under both normal and abnormal conditions are given in section III to validate the performance of the proposed control strategies. Finally section IV draws the conclusions.

II. CONTROL STRATEGY

A. Control Target of the VSC-MTDC System

As shown in Fig.1, a typical configuration, which consists of two wind farm VSCs (WVSCs) and two GSVSCs, is used to investigate the MTDC system. It is easy to extend it to the systems with more terminals according to similar principles. The wind turbines in the two offshore wind farms are considered to be connected together by local AC networks. The two WVSCs convert AC to DC and then the DC cables transmit the total connected power to the onshore GSVSCs. The two GSVSCs then convert the dc voltage to ac voltage and transmit the power to the AC grids. The two WVSCs implement frequency and AC voltage control at the point of common connection (PCC) with wind farms. Each

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GSVSC is equipped with an inner current controller and an outer DC voltage regulator. In addition they can also control the AC voltage or reactive power flow.

Fig. 1. A four terminal MTDC system

Under normal operation, the DC voltage of MTDC system must be maintained at a set value within a limited range. Abnormal DC voltage can disrupt the normal operation and even cause the trip of the system. A stable DC voltage indicates that the target of power balancing has been achieved among the multi-terminals. Therefore, the two WFSVCs are controlled to provide a constant AC voltage for the PCCs with wind farms. The control target of the two GSVSCs are designed to control the DC voltage to ensure the power generated by the offshore wind farms can be transmitted to the two AC grids and to dispatch the power between the two AC grids at a set ratio. Since the control of the WFSVCs is simple and clear, this paper focuses on the control of the two GSVSCs.

B. V-I Droop Characteristics

Fig. 2. DC equivalent circuit for the MTDC

Fig. 2 shows the steady state DC equivalent circuit of the MTDC system shown in Fig. 1. $R_1 \sim R_4$ represent the equivalent DC resistances of DC cable 1~cable 4, respectively. $V_{dc1} \sim V_{dc4}$ and $I_{dc1} \sim I_{dc4}$ are the responding DC voltages and currents of the four VSCs. For GSVSC1 and GSVSC2, the relationship between the DC voltages are given by:

$$V_{dc1} = V_{c2} - I_{dc1} R_1 \quad V_{dc2} = V_{c2} - I_{dc2} R_2 \quad (1)$$

where V_{c2} is the voltage of the common point as shown in Fig. 2. According to (1), following equation can be obtained:

$$V_{dc2} = V_{dc1} + I_{dc1} R_1 - I_{dc2} R_2 \quad (2)$$

The control method proposed in this paper is based on the DC V-I droop characteristics of the two GSVSCs, as shown in Fig. 3. According to Fig. 3, the DC voltage can be obtained by:

$$V_{dc1} = V_{min} + k_1 I_{dc1} \quad V_{dc2} = V_{min} + k_2 I_{dc2} \quad (3)$$

where V_{min} is the minimum DC voltage set by the system operator and k_1 and k_2 are the slopes of the V-I characteristics of GSVSC1 and GSVSC2, respectively. The control strategies are designed to dispatch the power between the two

GSVSCs (AC grids) at a set ratio represented by n . Because the DC voltages are approximately equal, the power sharing ratio can be expressed as:

$$\frac{P_1}{P_2} = n = \frac{I_{dc1} V_{dc1}}{I_{dc2} V_{dc2}} \approx \frac{I_{dc1}}{I_{dc2}} \quad (4)$$

Substituting (3) into (2):

$$V_{dc2} - V_{dc1} = k_2 I_{dc2} - k_1 I_{dc1} = I_{dc1} R_1 - I_{dc2} R_2 \quad (5)$$

Then substituting (5) into (4):

$$\frac{I_{dc1}}{I_{dc2}} = \frac{R_2 + k_2}{R_1 + k_1} = n \quad (6)$$

That is:

$$k_2 = n k_1 + n R_1 - R_2 \quad (7)$$

Equation (7) indicates that if the value of R_1 and R_2 are known, the value of k_1 and k_2 can be adjusted to get the required power sharing ratio n .

Fig. 3. V-I droop characteristics of GSVSCs

C. Control Strategies of GSVSCs

As the operation and control of VSC-HVDC have been well studied in [8]-[9], this paper focuses on the DC voltage control and the principle of power dispatch of MTDC system. Fig. 4 shows the simplified control systems of each GSVSC. A proportional controller is used instead of the usual PI controller to control the DC voltage because there will be a difference between the DC voltage, V_{dc} , and its reference value, V_{dcref} . V_{dc} is designed to change based on the V-I droop characteristic of each GSVSC and V_{dcref} is set as the minimum DC voltage which is corresponding to V_{min} in (3). The control outputs, i_d^* and i_q^* , are the reference value for the d -axis and q -axis component of the grid current respectively, which are associated with the active and reactive power. The inner current control loop is designed to regulate i_d and i_q to track i_d^* and i_q^* respectively and produce the d -axis and q -axis reference voltage, V_{dref} and V_{qref} , for controlling the GSVSCs.

The proportional gain is k_p . Based on the control systems as shown in Fig. 4, the relationship between V_{dc} and V_{dcref} can be obtained in order to associate them with the V-I droop characteristics of GSVSCs and the relationship can be expressed as:

$$V_{dcref} - V_{dc} = -\frac{i_d^*}{k_p} = -\frac{i_d}{k_p} = -\frac{i_d}{I_{dc}} * \frac{I_{dc}}{k_p} \quad (8)$$

In the rotating reference frame, the d -axis voltage V_d is

aligned with the phase voltage V_a , and the q -axis voltage V_q is zero. When the quadrature Park transformation is used,

ignoring the power loss, the power balance equation of each GSVSC can be expressed as:

Fig. 4. Control systems of each GSVSC

$$P = V_{dc} I_{dc} = V_d i_d \quad (9)$$

For the pulse width modulation (PWM) control, the modulation index is:

$$M = \frac{\sqrt{2}V_a}{V_{dc}/2} \quad (10)$$

Thus, the ratio of I_{dc} and i_d is given by:

$$\frac{I_{dc}}{i_d} = \frac{V_d}{V_{dc}} = \frac{\sqrt{3}/2 * \sqrt{2}V_a}{V_{dc}} = \frac{\sqrt{6}}{4} * \frac{\sqrt{2}V_a}{V_{dc}/2} = \frac{\sqrt{6}}{4} M = k_c \quad (11)$$

In (11), k_c is a constant value which is proportional to M . Substituting (11) into (8):

$$V_{dcref} - V_{dc} = -\frac{1}{k_c} * \frac{I_{dc}}{k_p} \quad (12)$$

Assuming $K = -1/k_c k_p$, equation (12) can be expressed as:

$$V_{dc} = V_{dcref} + KI_{dc} \quad (13)$$

This is the actual V - I characteristic of each GSVSC. Comparing (13) with (3), it is obvious that V_{dcref} is corresponding to V_{min} and K is corresponding to slope k_1 or k_2 . Thus, according to (7) and (13), a conclusion can be drawn that by adjusting the proportional gain k_p to regulate the value of K of each GSVSC, the power sharing ratio n can be controlled to the pre-set value. In summary, n is determined by the proportional gain k_p of each GSVSC.

III. SIMULATION RESULTS

The four terminals VSC-HVDC system, shown in Fig.1, was simulated using PSCAD/EMTDC. There are two 200 MW wind farms connected to the VSC-MTDC network. The four VSCs employ the two-level configuration with a switching frequency of 3.2 kHz. Each converter is rated at 300MW. The rated DC voltage is 300 kV. DC cables were used to connect the four terminals and each cable has the equivalent parameters of $R = 0.2\Omega$, $L = 0.005H$ and $C = 5\mu F$. The reference dc voltage, V_{dcref} , of each GSVSC is set to 0.95pu (285 kV).

A. Step Change of Wind Farms

Step changes of the input wind farm power were used to evaluate the control strategies. The injected power from wind farm 1 was changed from 0.5pu to 1.0pu at 7s and recovered to 1.0pu at 12s, while the injected power from wind farm 2 remained 1.0pu all the time. Regulate k_p of each GSVSC to set

$k_1 = k_2 = 30$. Thus the power sharing ratio $n = 1$. Fig.5 shows the simulation results.

(a) DC current of GSVSCs

(b) DC voltage of GSVSCs

(c) Active power of wind farms

(d)Active power of AC grids

Fig. 5. Simulation results with variable wind power

As illustrated in Fig.5 (a) and (b), the DC currents of GSVSCs and the DC voltages changed with the wind power. The DC voltages were maintained at nearly a constant value when the system came back to steady state, which means the power balancing is achieved. The total injected wind power was shared equally by AC grid 1 and 2, both of which are 142.5 MW in the period of 0-6s and the period of 14-16s. The total shared power was slightly less than the injected power due to the power loss caused by VSCs and DC cables. It can be seen that the MTDC system has a good dynamic response when the injected wind farm power is changed.

B. Step Change of Power Sharing Ratio

Step changes of power sharing ratio were used to validate the power dispatch theory deduced above and further evaluate the control strategies. Regulate k_p of each GSVSC to set the value of power sharing ratio n according to the previously explained theory. Wind farm 1 provided 1.0pu power and wind farm 2 provided 0.5pu power all the time. The power sharing ratio changed from $n=2$ to $n=1.5$ at 6s and changed back to $n=2$ at 11s. Fig.6 shows the simulation results.

(a) DC current of GSVSCs

(b)DC voltage of GSVSCs

(c)Active power of wind farms

(d)Active power of AC grids

Fig. 6. Simulation results with variable power sharing ratio

As shown in Fig.6, the DC currents of GSVSCs varied with the change of the power sharing ratio. The DC voltages were almost unchanged. The total injected power was 300 MW. AC grid 1 and 2 absorbed 189.8 MW and 95.2 MW, respectively, between 0-6s and 12-16s. The actual power sharing ratio was 1.994. While 171.3 MW and 114.7 MW were absorbed by AC grid 1 and 2, respectively, during 7-11s. The actual power sharing ratio was 1.493. Simulation results show that the actual power sharing ratio is almost identical with the theoretical value and the dynamic response is satisfactory.

C. Simulation Results Under a Three Phase Fault

A three phase to ground fault was applied at 4s for duration of 0.2s on the primary side of GSVSC2's coupling transformer. The injected power from wind farm 1 and wind farm 2 was 1.0pu and 0.5pu, respectively. The power sharing ratio n was set to 2.

(a) DC current of GSVSCs

(b)DC voltage of GSVSCs

(c) Active power of wind farms

(d) Active power of AC grids

Fig. 7. Simulation results with a three phase fault

As shown in Fig. 7, before the fault was applied, AC grid 1 shared a power of 190 MW and AC grid 2 shared a power of 96 MW. When the fault occurred at 4s, the power absorbed by AC grid 2 decreased to zero quickly and the surplus power caused by the power loss of GSVSC2 transferred to GSVSC1, thus the power absorbed by AC grid 1 increased. The DC voltages rose sharply. Especially the voltage of GSVSC2 rose to 325 kV at 4.1s, which is 8.33% higher than the nominal voltage. The system recovered to normal operation within 1.5 second.

IV. CONCLUSIONS

A typical four-terminal VSC-HVDC system was built for integrating large offshore wind farms. The operation principles and control strategies of the system were described. The two WFVSCs were controlled to establish a constant AC voltage and frequency for the PCCs with wind farms. DC voltage control based on the $V-I$ characteristics of GSVSCs was designed to regulate DC voltage and coordinate power sharing between the two AC grids. The relationship between the power sharing ratio and proportional gain was described. The proposed control method allows multiple converters to control the DC voltage and dispatch the power at a set ratio in real time without fast communications. Simulations results under variable wind power and power sharing ratio have been presented to validate the performance of the proposed control strategies. The results show satisfactory dynamic response. The system can maintain stability and show good performance in a certain degree during large disturbance caused by three phase to ground fault on the AC grid.

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