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Study of Coordination Control for VSC-MTDC Under New Developing Trend

Zhou Li[1], Yazhou Li[1,*], Zhanruo Pei[1], Yan He[1] and Yuping LU[1]

[1]School of Electrical Engineering, Southeast University, Nanjing 210096, China

[*]Email: liyazhou93@126.com

Abstract. With the developing of voltage source converter based multi-terminal dc transmission (VSC-MTDC) technology, DC grid of meshed topology is the trend of VSC-MTDC; moreover, it will be widely used for large scale renewable energy integration. For DC grid of meshed topology, the control aspect is of great importance, while the randomness and volatility of renewable energy will affect the stability of DC grid. The control stability of the VSC-MTDC, especially the control of DC voltage, will face new challenges. This paper focus on the developing trend of VSC-MTDC, the control requirements of DC grid of meshed topology and the effects of large scale renewable energy to the VSC-MTDC are analysed. And mainstream coordinating control strategies under the new situation are compared through the way of theoretical analysis. Simulations based on PSCAD/EMTDC are carried out in a five-terminal meshed VSC-MTDC system with an isolated wind farm, a passive network and three ac synchronized power grids, proving the accuracy of theoretical analysis. Then control characteristics and applicability of the coordinating control strategies for meshed VSC-MTDC with large scale renewable energy integration are concluded.

1. Introduction

Voltage Source Converter based High Voltage Direct Current (VSC-HVDC), as an important technology in the smart grid, has been in a rapid development recently [1, 2]. Its advantages include the independent control of active and reactive power, continuous ac voltage regulation, black-start capability and the ability to reverse power without voltage polarity reversal which facilitates the constitution of multi-terminal HVDC (VSC-MTDC) systems [2]. Owing to the ability of continuous ac voltage regulation, the VSC-HVDC technology is widely applied for isolated renewable energy integration. VSC connected to isolated renewable energy grid has to maintain ac voltage and loses the control of transmitted power [3]. And then, active power fluctuations of ac girds will affect power flow in DC grid which increases the control difficulty of DC voltage.

The topological structure of VSC-MTDC systems can be divided into basic topologies, namely, radial and meshed topologies [1-4]. DC grid of meshed topology which has high operational flexibility and reliability is the trend of VSC-MTDC. However, compared with radial topology which is simple in construction, the DC voltage control of meshed VSC-MTDC system is more difficult. It is necessary to study the control characteristics of the mainstream coordinating control strategies in DC grid of meshed topology. For VSC-MTDC systems, master-slave control and DC voltage droop control are two mainstream coordinating control strategies [5, 6]. The existing comparison between the two types of control strategies focuses on the dependency level on communication, while the analysis and comparison of the dynamic and steady-state characteristics of the VSC-MTDC system adopting different control strategies is insufficient.

Aiming at the developing trend of VSC-MTDC, this paper analyses the impact of isolated renewable energy integration on VSC-MTDC system and dc voltage control characteristics of meshed VSC-MTDC system. Steady-state and dynamic characteristics of two dominant coordinative control strategies, master-salve control and droop control, are analysed from mechanism. Applicability of the coordinating control strategies for meshed VSC-MTDC are concluded. Finally, a meshed VSC-MTDC system with renewable energy integration is formed in the PSCAD/EMTDC software, and theoretical analysis of the coordinating control strategies is verified by results of simulation examples.

2. New developing trend of VSC-MTDC

2.1. Control requirements of Meshed DC gird

For a radial VSC-MTDC system, when the DC voltage of central station is stable, the transmission power of other stations only depends on their DC voltage, respectively. However, for a meshed VSC-MTDC system with *n* stations, assuming that there are *m* stations connected to VSC1, the relationship between the power transmitted from VSC1 to the DC grid (P_{dc1}) and the DC voltage (U_{dci}) is:

$$P_{dc1} = U_{dc1}\left(\frac{U_{dc1}}{r_{12}//r_{13}//...//r_{1m}} - \frac{U_{dc2}}{r_{12}} - \frac{U_{dc3}}{r_{13}} - ... - \frac{U_{dcm}}{r_{1m}}\right) \tag{1}$$

Where r_{1m} is the equivalent resistance of the DC line from VSC1 to VSC*m*. *j*=2, 3, …, *m*.

Equation (1) indicates that the power transmitted by the VSC1 is affected by the DC voltage of each adjacent station. Therefore, if the transmitted active power of a certain station is changed by adjusting its DC bus voltage, it will inevitably affect the transmitted active power of other stations in the system, thereby affecting the DC voltage of other converter stations. Compared with the radial structure commonly used in existing VSC-MTDC engineering, the DC voltage of each VSC in meshed HVDC grids is closely related, which increase the complexity of DC voltage control.

2.2. Effect of large-scale renewable energy integration

VSC adopting amplitude-phase control can provide voltage support independent from the transmitted active power, which makes it an attractive solution for large scale renewable energy integration. The transmission power of the amplitude-phase control station satisfies:

$$P_s = P_{dc} + \Delta P_c \tag{2}$$

Where P_s is the power of ac grid, ΔP_c is the converter losses, P_{dc} is power transmitted to DC gird.

Equation (2) indicates that the renewable energy power is passively transmitted to the DC networks without control. As a result, if the VSC-MTDC system fails to absorb the random changes of new energy power bases in real time, the change in new energy power will cause the change in the dc grid voltage, thus affecting the stability of the DC grid. Therefore, the VSC-MTDC system which is used for renewable energy integration has high rigid requirement on the active power balancing capability.

2.3. New requirements of control characteristics of VSC-MTDC system

Most of the VSC-MTDC systems that have been applied are radial topologies, and then most of the existing research is based on radial VSC-MTDC systems. Furthermore, the control characteristics of control strategies are mainly analysed through the way of simulation and lacks theoretical analysis. With droop control and master-slave control considered as dominant control strategies, it is necessary to analyse the control characteristics of the two control strategies from the mechanism.

3. Control characteristics of master-slave control strategy under new situation

In master-slave control structure, one DC voltage control station acts as master station to maintain constant DC voltage while other stations act as slave stations, tracking active power references.

Assume that a meshed VSC-MTDC system contains n stations, station 1 acts as master station, station 2 to (m-1) adopt constant active power control, and other stations adopt amplitude-phase control.

3.1. Steady-state analysis of master-slave control strategy
Power fluctuation occurs in the VSC-MTDC system. After the system reaches is steady, neglecting inverter and line losses, the transmitted power of stations satisfies equation 3. The unbalanced power of the DC grid is absorbed by the master station and DC grid operates at standard voltage. The slave station transmits active power according to the power reference value.

$$\sum\left(P_1,P_{ref2},\dots,P_{refm},P_{m+1},\dots,P_n\right)=0 \tag{3}$$

3.2. Dynamic analysis of master-slave control strategy
Taking the phase of AC voltage at the point of common coupling as d-axis based on the synchronously rotating dq-frame, then $u_q=0$, $u_d=U_s$, $P_s=U_s i_{sd}$. When the AC voltage of PCC is stable, the transmitted power variation of VSC depends entirely on d-axis current variation.

As shown in figure 1, the PI-based controller generates a reference value of the d-axis current (i_{dref1}) by using the difference between reference voltage (U_{dcref1}) and the actual DC voltage (U_{dc1}).

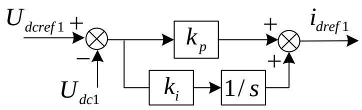


Figure 1. Block diagram of DC voltage control

The correspondence between DC voltage variation and i_{dref1} variation is:

$$\Delta i_{sdref1}=-\left(k_p+\frac{k_i}{s}\right)\Delta U_{dc1} \tag{4}$$

Formula (4) indicates that the change rate of i_{dref1} of a dc voltage control (DVC) station is only related to the change rate of DC voltage. After the DC power flow changes, the unbalanced power of the DC grid charges or discharges the equivalent capacitance of each station to change the DC grid voltage. The DVC station is only involved in the regulation of the DC grid flow after the change of DC voltage, hence its response speed is not fast enough. Furthermore, only one station in the master-slave control regulates the DC power flow, so the power regulation speed of the master-slave control is slow, and the DC system power variation will cause large DC voltage fluctuations.

4. Control characteristics of droop control strategy under new situation

Voltage droop control is a kind of multi-point dc voltage control, which is a technique that enables all droop control converter stations to regulate the dc voltage. Assume that a meshed VSC-MTDC system contains n converter stations, station 1 to m adopt DC voltage droop control, station m to (m+k) adopt constant active power control, and other stations adopt amplitude-phase control.

4.1. Steady-state analysis of droop control strategy
Power fluctuation occurs in the VSC-MTDC system. The relationship between the change of active power of VSC and the change of the DC voltage is:

$$\Delta U_{dc}=U_{dci}^{'}-U_{dci}^{0}=K_i(P_i^{'}-P_i^{0})=K_i\Delta P_i \tag{5}$$

Where U_{dci}^{0} is the initial voltage of VSCi, $U_{dci}^{'}$ is the stabilized voltage of VSCi, P_i^{0} denotes the initial power of VSCi, and $P_i^{'}$ is the stabilized active power of VSCi.

After the system is stable, the transmitted power of constant active power control or amplitude-phase control stations is unchanged, then the total variation of the transmitted power of all voltage droop control stations is the initial unbalanced power (P_{Σ}^{0}). Therefore:

$$P_{\Sigma}^{0}=\sum\left(P_1^0,P_2^0,\ldots,P_m^0,P_{m+1},\ldots,P_n\right)=\sum_{i=1}^{m}(P_i^{'}-P_i^0)=\Delta U_{dc}\sum_{i=1}^{m}\frac{1}{K_i} \quad (6)$$

Taking into account of equations (5) to (6), $U_{dci}^{'}$ and $P_i^{'}$ can be calculated as

$$U_{dci}^{'}=U_{dci}^{0}+P_{\Sigma 0}\left(\sum_{i=1}^{m}\frac{1}{K_i}\right)^{-1} \quad (7)$$

$$P_i^{'}=P_i^0+P_{\Sigma 0}\left(K_j\sum_{i=1}^{m}\frac{1}{K_i}\right)^{-1} \quad (8)$$

Equation (7), (8) indicates that the unbalanced power at the initial moment of the DC system causes the DC voltage and the transmission power of droop control station to deviate from the initial state. Therefore, for VSC-MTDC systems that use voltage droop control, the droop converter stations lose the control accuracy of transmission power.

4.2. Dynamic process analysis of droop control strategy
According to the control structure, as shown in figure 2, the i_{dref1} variation value can be indicated as:

$$\Delta i_{drefi}=\left(k_p+\frac{k_i}{s}\right)(-K_i\Delta P_i-\Delta U_{dci}) \quad (9)$$

The transmitted power of droop control station has same variation trend as the DC voltage. From equations (4), (10), it can be seen that, with same DC voltage variation, the d-axis current regulating speed in droop control is faster than constant DC voltage control, and then power regulating speed of voltage droop station is faster. Furthermore, in droop control, all voltage droop control stations participate in power balance, so the dynamic stability of the DC voltage is better.

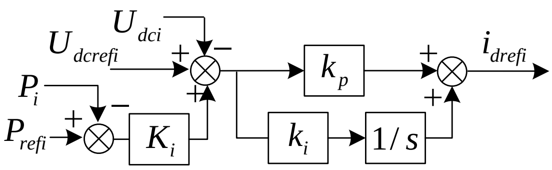


Figure 2. Block diagram of voltage droop control.

4.3. Comparison of control characteristics of mainstream control strategies
Based on the above analysis, the control characteristics of mainstream control strategies are summarized as Table 1.

Table 1. Comparison of control characteristics of mainstream control strategies.

	Master-salve control	Droop control
Power balance station	Master station	Droop control stations
Speed of power response	Slow	Rapid
Accuracy of transmission power	High	Low
Dynamic voltage characteristics	Poor	Good
Steady-state voltage value	Rated voltage	Voltage Deviation
Communication requirement	High dependence	No dependence
Controller design difficulty	Simple	Droop constant is difficult to set

Result of analysis demonstrates that the droop control strategy has good dynamic stability of the DC voltage, however sacrificing the accuracy of power control. The master-slave control can maintain the accuracy of power control but has poor dynamic stability of the DC voltage.

5. Simulation Results

5.1. Simulation system

In this paper, a five-terminal VSC-MTDC simulation model, as shown in figure 3, is established using PSCAD/EMTDC. VSC1 is used for wind farm (WF1) integration and VSC3 is used to feed passive load. VSC2, VSC4, and VSC5 connect to 500kV AC synchronized power grids, respectively.

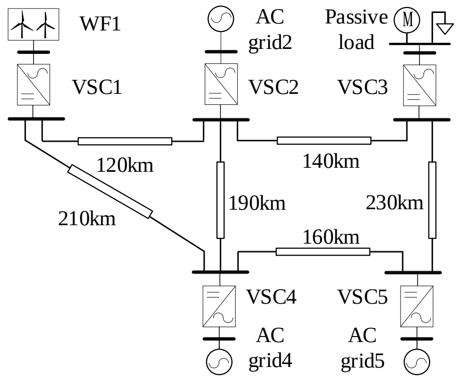


Figure 3. Block diagram of the main circuits for the simulated MTDC system.

VSC1 and VSC3 both adopt amplitude-phase control. Wind farm 1 (WF1) is rated at 400 MW. The initial passive load connected to VSC3 is 550MW. In master-slave control, VSC4 acts as master station, and VSC2 and VSC5 act as slave station; in voltage droop control, VSC2, VSC4, and VSC5 all adopt voltage droop control. The parameters of each VSC are shown in table 2.

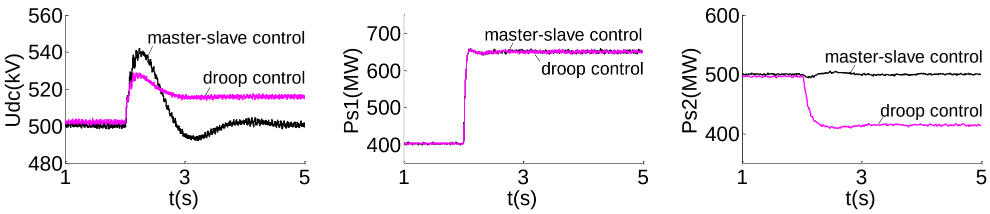
Table 2. Control parameters of VSC-MTDC system.

		VSC1	VSC2	VSC3	VSC4	VSC5
P_{max}/MW		750	750	0	750	0
P_{min}/MW		0	0	-750	-750	-750
DC voltage/kV		500	500	500	500	500
AC bus voltage /kV		220	500	220	220	500
Droop constant (kV / MW)		—	0.1	0.1	—	0.1
P_{ref}/MW	Master-slave control	—	500	—	—	-700
	DC voltage droop control	—	500	-150	—	700

Two simulation examples are designed to verify the theoretical analysis of coordinating control strategies in section 4.

5.2. Case 1: Control performance during a sudden increase of wind power

Initially, all stations are in steady state, following the setpoints of Table 1. At t = 2s, power of wind farm1 is increased by 300MW. Simulation waveforms are shown in Figure 4.



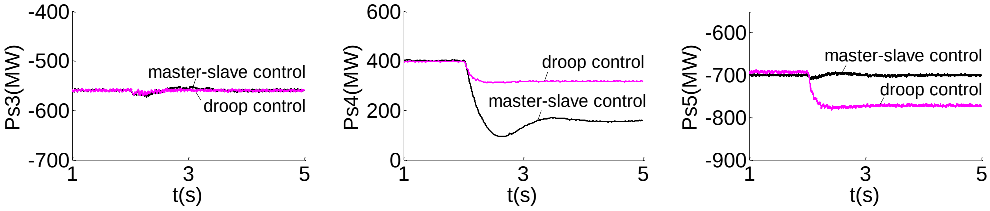


Figure 4. Simulation results of VSC-MTDC system during a sudden increase of wind power

From figure 4, it is shown that power fluctuation of WF1 causes a high overshoots of DC voltage (1.08p.u.) in the master-slave control. After the system reaches a new steady state, initially unbalanced of DC grid is entirely absorbed by the VSC4. DC grid voltage is returned to reference value and all salve stations track the power reference value accurately.

In droop control, all droop control stations participate in power regulation and respond quickly, the power transmitted by VSC2, VSC5 and VSC6 increase 63MW, 63MW, and 125MW, respectively. The power variation of droop control stations is in accord with formula (8), and DC gird voltage deviates from the reference value.

5.3. Case 2: Control performance during a sudden increase of passive load

Initially, all stations are in steady state. At t = 2s, passive active load is reduced by 300MW. Throughout the process, all stations following the setpoints of Table 1.

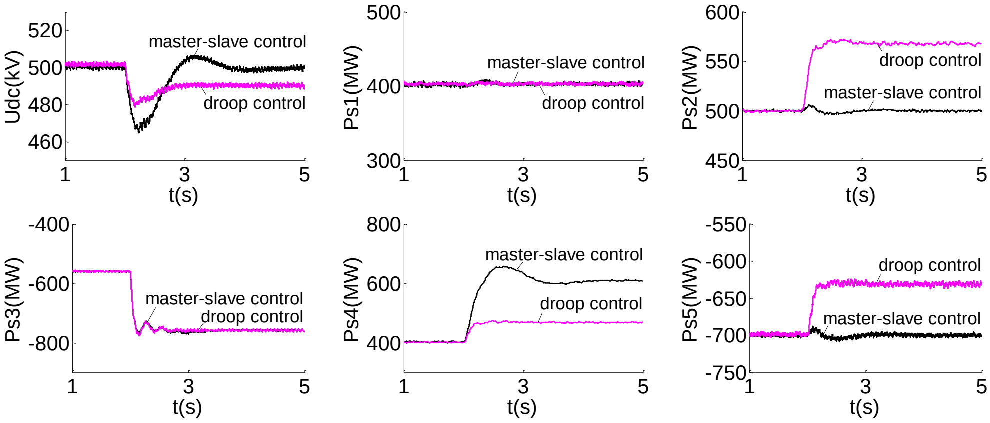


Figure 5. Simulation results of VSC-MTDC system during a sudden increase of passive load

Figure 5 shows that, in the master-slave control, the unbalanced power of DC grid is absorbed by the VSC2 in 1.8s with high overshoots in DC voltage. After the system is steady, voltage of DC grid restores standard value and all salve stations maintain the power control accuracy.

In droop control, the system reaches a new stable state in 1s. The power variation of each droop control station accords with formula (8). Furthermore, all stations exhibit a small DC voltage overshoot. However, the DC gird voltage deviates from the reference value and the droop control stations lose the control accuracy of transmission power.

The results agree with the summary of control characteristics of coordinating control strategies for meshed VSC-MTDC in table 1, which verify the accuracy of theoretical analysis in section 4.

6. Conclusion

With the increase of renewable energy integration and complication of topology, the control stability of the VSC-MTDC, especially the control of DC voltage, will face new challenges. While there are some deficiencies in mainstream coordinative control strategies which should draw attention. Results of analysis and simulation demonstrate the master-slave control maintains the accuracy of power control but has poor dynamic stability of the DC voltage. On the contrary, droop control strategy sacrifices the accuracy of transmitted power to achieve good dynamic stability of the DC voltage.

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References

[1] Liang J Gomis-Bellmunt O and Hertem D V 2016 HVDC grid layouts: For Offshore and Supergrid of the Future HVDC Grids.
[2] Xu L and Yao L 2011 Dc voltage control and power dispatch of a multi-terminal hvdc system for integrating large offshore wind farms. *(Iet Renewable Power Generation vol 53)* pp 223-233.
[3] Koutiva X I, Vrionis T D, Vovos N A and Giannakopoulos G B 2006 Optimal integration of an offshore wind farm to a weak ac grid *(IEEE Transactions on Power Delivery vol21)* pp 987-994.
[4] Stamatiou G and Bongiorno M 2017 Power-dependent droop-based control strategy for multi-terminal hvdc transmission grids *(Iet Generation Transmission & Distribution vol 11)* pp 383-391.
[5] Prieto-Araujo E, Bianchi, F D, Junyent-Ferre A and Gomis-Bellmunt O 2011 Methodology for droop control dynamic analysis of multiterminal vsc-hvdc grids for offshore wind farms. *(IEEE Transactions on Power Delivery vol 26)* pp 2476-2485.
[6] Cao J, Du W, Wang H F, and Bu S Q 2013 Minimization of transmission loss in meshed ac/dc grids with vsc-mtdc networks. *(IEEE Transactions on Power Systems vol28)* pp 3047-3055.