Optimal Coordination Voltage Control of Hybrid AC/DC Grids Considering Control of HVDC System

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Abstract. With the wide application of UHVDC in long-distance and large-capacity power transmission, the current power grid has developed into a complex AC-DC deep coupling system, which poses a serious challenge to the voltage safety control of the system. Based on the voltage sensitivity of AC/DC system, this paper presents a voltage optimization control method for integrated coordination of AC/DC system control variables. In this control method, a linear constrained quadratic optimization model with minimum control cost is constructed to coordinate the control variables of AC/DC system and correct the voltage amplitude deviation. The potential of UHVDC system to participate in voltage control is studied by optimizing the control quantity of rectifier side and inverter side converters. The simulation results of AC/DC hybrid system show that the proposed optimal control method can effectively coordinate the control quantity of AC/DC system and ensure the voltage operation in a safe range.

1. Introduction
The line-commutated converter based high voltage direct current (LCC-HVDC) has become one of the main forms of power transmission from energy base to load center because of its large long-distance transmission capacity and strong asynchronous interconnection ability. The scale of UHVDC transmission has increased significantly, and the current power grid has developed into a complex AC-DC deep coupling system. A large number of LCC-HVDC system access brings serious challenges to voltage stability analysis and control of AC and DC systems [1-3]. The main manifestations are as follows: 1) LCC-HVDC system converter absorbs a large amount of reactive power. When the reactive power reserve of the system is insufficient, the voltage instability caused by the accident is prone to occur. 2) The expansion of the scale of LCC-HVDC system weakens the strength of AC system and increases the risk of voltage stability. 3) A large amount of new energy power is transmitted to the receiving load center through the DC system, and the high energy-consuming units of the receiving system are eliminated, which reduces the reactive power/voltage regulation capability of the receiving system. Furthermore, with the continuous growth of load, the problem of voltage stability in AC and DC systems becomes more prominent, and voltage safety control strategies for AC and DC systems are urgently needed. Based on this, this paper studies the optimal control of coordinated AC/DC system control resources, such as generator-side voltage control, reactive power compensation, rectifier-side converter and inverter-side converter control.
For AC systems, a large number of literatures have studied the static voltage optimization control method. One method is to establish an optimal control model for voltage correction control [4-6], taking into account all controllable variables. In [4], the interior point method is used to optimize the system control variables and prevent voltage collapse. In [6], a non-linear programming model with minimum control cost and minimum voltage stability margin constraints of system requirements is established, and the optimal voltage stability correction control based on primal-dual interior point method is proposed. Sensitivity-based optimal voltage control is another important method [7-10]. The most effective control variables are determined by sensitivity analysis. Based on the control variables, the optimization model of voltage control is established, which reduces the complexity and control cost of the optimization model, improves the calculation speed and can be more effectively applied to online voltage safety control. [7] builds a linear programming optimal control model based on sensitivity to prevent system voltage collapse from two aspects of preventive control and corrective control. [8] presents a sensitivity-based optimal control method for low-voltage load shedding, which restores the voltage to the target voltage after load shedding control and minimizes the load shedding. Based on sensitivity analysis, the reactive power/voltage sensitivity of each station is calculated in real time, and the optimal control strategy of reactive power and voltage is designed to eliminate the overrun of system voltage [9].

Although a large number of literatures have studied the voltage optimal control of AC system, few studies have been done on the voltage optimal control of AC and DC system, especially the LCC-HVDC system as a control means to improve the voltage stability of the system. In [11], a quadratic programming model with non-linear constraints is established to determine the control method of static voltage stability for AC/DC system. The converter transformer ratio of DC system is considered as the control variable to participate in voltage stability control. In [12], the primal-dual interior point method is applied to optimize reactive power flow in AC/DC systems. [13] establishes a linear optimization model to coordinate reactive power allocation of AC/DC systems to improve voltage stability of AC/DC systems. Because of the fast regulation ability of HVDC converter, the additional control of HVDC system is an important control means to improve the stability of the system. [14-15] improve the power modulation of HVDC system as an additional control for transient stability. [16-17] designs a HVDC system to provide additional damping control to improve the system's damping capacity and suppress power oscillation. However, the work of HVDC system rectifier side and inverter side converters in static voltage control is seldom introduced.

Based on sensitivity calculation, this paper establishes a voltage optimization control model for coordinated AC and DC systems to correct the voltage amplitude and ensure the voltage stability of the system. With the objective of minimizing the control cost, the linear constrained quadratic programming problem is constructed. The control variables of AC and DC systems are coordinated comprehensively, and the ability of HVDC system converters to participate in voltage stability control is explored. Finally, the simulation results show that the proposed method can effectively improve the voltage stability of AC and DC systems and give full play to the HVDC system's ability to participate in voltage control.

2. Voltage sensitivity of AC/DC system

2.1. Quasi-steady-state model of HVDC system

The line diagram of to-point HVDC system is shown in Figure 1. The superscript R, I are represents the rectifier side and the inverter side respectively. The subscript ac, d are represents AC and DC respectively.

Figure 1. Line diagram of to-point HVDC system.

The quasi-steady state equation of HVDC system is:
\[
V_{d0} = (3\sqrt{2}/\pi k)v_{d0}^e, \quad V_{do} = (3\sqrt{2}/\pi k)v_{do}^e
\]
\[
V_d^e = V_{do}^e \cos \alpha - (3/\pi)X^d I_d
\]
\[
V_i^e = V_{do}^e \cos \gamma - (3/\pi)X^i I_i
\]
\[
I_d = (V_d^e - V_i^e)/R_d
\]
\[
P_d^e = V_d^e I_d
\]
\[
Q_d^e = I_d\sqrt{(V_d^e)^2 - (V_i^e)^2}
\]
\[
P_i^e = V_i^e I_i
\]
\[
Q_i^e = I_d\sqrt{(V_i^e)^2 - (V_d^e)^2}
\]

Where \( V_{d0}^e \) and \( V_{do}^e \) are no-load DC voltage on rectifier side and inverter side respectively. \( V_d^e \) and \( V_i^e \) are DC voltage of rectifier side and inverter side respectively. \( V_{d0}^e \) and \( V_{do}^e \) are the commutation bus voltage of rectifier side and inverter side respectively. \( k^e \) and \( k^i \) are the converter transformer ratio of rectifier side and inverter side respectively. \( X^e \) and \( X^i \) are the equivalent commutation resistance of rectifier side and inverter side respectively. \( R_d \) is the DC line resistance. \( I_d \) is the DC current. \( \alpha \) and \( \gamma \) are the trigger angle of the rectifier and the arc extinguishing angle of the inverter respectively. \( P_d^e \) and \( Q_d^e \) are the active power and reactive power absorbed by the commutating buses on the rectifier side respectively. \( P_i^e \) and \( Q_i^e \) are the active power generated by converter buses on the inverter side and reactive power absorbed respectively.

In order to ensure the stable operation of the HVDC system, the rectifier side converter and the inverter converter need to cooperate reasonably. The control modes of HVDC system operation include: constant power control on rectifier side with constant arc extinguishing angle control on inverter side; constant current control on rectifier side with constant arc extinguishing angle control on inverter side; constant power control on rectifier side with constant voltage control on inverter side; constant current control on rectifier side with constant voltage control on inverter side. In practical applications, the HVDC system usually transmits constant power according to scheduling arrangement. The HVDC system often adopts the mode of constant power control on rectifier side and arc extinguishing angle control on inverter side. According to the different control modes of rectifier side and inverter side, combined with the steady-state equation of the above-mentioned HVDC system, the converter bus power can be expressed as follows:

\[
P_d^e = h^e[V_d, V_i, u^e, u^i]
\]
\[
Q_d^e = g^e[V_d, V_i, u^e, u^i]
\]
\[
P_i^e = h^i[V_d, V_i, u^e, u^i]
\]
\[
Q_i^e = g^i[V_d, V_i, u^e, u^i]
\]

Where \( h \) and \( g \) are the mapping function relation. \( u^e \) and \( u^i \) are the control mode of rectifier and inverter sides respectively. For example, the constant power control on the rectifier side is combined with the constant arc extinguishing angle control on the inverter side. \( u^e \) is the constant power \( P_{order} \) for arrangement. \( u^i \) is the constant extinction angle \( \gamma_{order} \).

2.2. Power flow equation of AC/DC system

The power flow equation of AC/DC system is formulated. If the DC system is equivalent to the injected power at the commutation bus, the power flow equation of AC/DC system can be expressed as follows:
Formula (6) ~ (8) is the power flow equation of AC/DC system.

2.3. Sensitivity calculation

Voltage sensitivity refers to the sensitivity relationship between the load node voltage and the control variables, which characterizes the control variable's ability to regulate the load node voltage. The greater the voltage sensitivity, the stronger the control ability of the control variable to the voltage, the more effective the control variable as a control means to adjust the system voltage. Through sensitivity calculation, control variables can be effectively screened, control costs can be reduced and control efficiency can be improved. Sensitivity calculation can be divided into two kinds of [18]: perturbation method and Jacobian matrix method. By adding a small disturbance to the control variables, the disturbed power flow solution is obtained. Based on the power flow solutions before and after the disturbance, the sensitivity calculation is carried out. Obviously, calculating the voltage sensitivity of each control variable requires two power flow solutions. For a system with many control variables, obtaining the voltage sensitivity of all control variables requires a lot of power flow calculation. Jacobian matrix method calculates the voltage sensitivity of control variables based on Jacobian matrix of power flow equation, which can easily solve the sensitivity of different control variables and improve the calculation efficiency. The general form of the power flow equation of AC/DC system can be expressed as follows:

\[ f(x,u)=0 \]  (9)

Where \( x \) are the state variables of AC/DC system, such as load node voltage and phase, \( u \) are the control variables of the system, such as generator terminal voltage, reactive power compensation, rectifier side constant power, inverter side constant arc extinguishing angle. Based on the implicit function derivation rule, when the change of control variable \( u \) is \( \Delta u \), the change of system state variable \( \Delta x \) is expressed as follows:

\[ \Delta x = \left( \frac{\partial f}{\partial x} \right)^{-1} \frac{\partial f}{\partial u} \Delta u = s_{xu} \Delta u \]  (10)

Where \( - \left( \frac{\partial f}{\partial x} \right)^{-1} \) is the Jacobian matrix for power flow equation. \( \frac{\partial f}{\partial u} \) is the partial derivatives of power flow equations to control volumes. \( s_{xu} \) is the sensitivity of control quantity to state quantity. When \( x \) is the load node voltage, \( s_{xu} \) is the voltage sensitivity which can be expressed as:
Through formula (11), the voltage sensitivity of the system and select control variables can be effectively determined.

3. Coordinated voltage optimal control for AC/DC systems

3.1. Voltage control of AC/DC system based on sensitivity

The main steps of the logic of coordinated voltage optimal control for AC/DC systems are as follows:

1) The dispatching center obtains power flow information of the system based on real-time system operation data.

2) Determining the load node of the minimum voltage amplitude of the system.

3) Determine whether the minimum voltage is less than the specified lower limit of voltage constraint (e.g., 0.9p.u.) and if so, proceed to step 4, otherwise continue to monitor the operation status of the system and maintain the control signal of the current control quantity unchanged.

4) Calculate the sensitivity of minimum voltage of load node to system control variables (including generator terminal voltage, reactive power compensation, rectifier side converter control of DC system and inverter side converter control, etc.).

5) Voltage optimization control step is established based on sensitivity. This step solves the transition control signal of control quantity in dispatching center by establishing optimization model (the control signal is not directly applied to control elements). The description of the optimization model will be described below.

6) Based on the transition control signal of the control variable determined in step 5), the power flow information of the system is recalculated to determine the minimum voltage of the system after applying the control signal.

7) Determine whether the minimum voltage is restored to the required voltage threshold (e.g., 0.95p.u.) and if so, issue the control instruction to the control element or return to step 4).

8) The control elements of the AC/DC system set their respective control values according to the control instructions.

3.2. Sensitivity-based optimization model for voltage control

The control variables in the optimization model include HVDC rectifier side power control, inverter side arc extinguishing angle control, generator terminal reference voltage control and capacitor compensation capacitor control. The objective of the model is to minimize the control cost, take into account the size constraints of control variables, and adjust the voltage amplitude with a fixed control step to meet the requirements of voltage recovery. The specific mathematical model is as follows:

$$\text{min } \eta(x) = \sum_{i \in a_1} \frac{\Delta u^k_i}{u^0_k} + \sum_{j \in a_2} \left( \frac{\Delta u^j_{i,j}}{u^0_{i,j}} \right)^2$$

$$+ \sum_{p \in a_4} \frac{\Delta V^p_i}{V^0_{i,p}} + \sum_{q \in a_3} \frac{\Delta B_{i,j}}{B^0_{i,j}}$$

The constraints are:

$$\min u^k_i \leq u^k_{i-1,j} + \Delta u^k_{i,j} \leq \max u^k_i \quad i \in a_1$$

$$\min u^j_{i,j} \leq u^j_{i-1,j} + \Delta u^j_{i,j} \leq \max u^j_{i,j} \quad j \in a_2$$

$$\min V^p_{i,p} \leq V^p_{i-1,p} + \Delta V^p_{i,p} \leq \max V^p_{i,p} \quad p \in a_4$$

$$\min B_{i,j} \leq B_{i-1,j} + \Delta B_{i,j} \leq \max B_{i,j} \quad i \in a_3$$

$$i \in a_3$$
\[
\Lambda_i = \sum_{i=1}^{N} \frac{x_i}{x_i} + \sum_{j=1}^{M} \frac{y_j}{y_j} + \sum_{k=1}^{L} \frac{z_k}{z_k} + \sum_{l=1}^{P} \frac{w_l}{w_l}
\]

(17)

Where \( k \) denotes step \( k \). \([\Delta u_{k,i}, \Delta u_{k,j}, \Delta V_{k,i}, \Delta B_{k,j}]\) is the decision variables, denoting the control quantity of rectifier side converter, inverter side converter, generator reference voltage control quantity and capacitor compensation control quantity respectively. \([u_{0,i}, u_{0,j}, V_{0,i}, B_{0,j}]\) is the initial value of control quantity. \( \alpha_R, \alpha_I, \alpha_G \) and \( \alpha_C \) represent rectifier-side converter set, inverter-side converter set, generator node set and capacitor compensation node set respectively. \( \alpha_h, \alpha_i, \alpha_r, \alpha_q \) represent the weights of different control variables respectively. Formula (13) ~ (16) denotes the upper and lower limit constraints of different control variables. Formula (17) is an equality constraint, which correlates the control variation with the voltage sensitivity. \( s_{k,i}, s_{k,j}, s_{k,p} \) and \( s_{k,q} \) represent the sensitivity of different control variables respectively. \( \Lambda_V \) represent the voltage control step size, such as \( \Lambda_V = 0.1 \). Constrained by equation (17), the optimal control model determines the control signal of the control variable with a fixed voltage control step until it meets the requirements of voltage control.

3.3. HVDC system participates in voltage optimal control

Section 3.2 coordinates the control quantity of AC/DC system to optimize the voltage control. As an important control method, HVDC system has significant applications in transient stability control and enhanced damping control. There is little research on the ability of HVDC system to participate in voltage control. Based on the optimization model of section 3.2, the model of HVDC additional voltage control can be expressed as follows:

\[
\min \eta(x) = \sum_{i=1}^{N} \omega_i \left( \frac{\Delta u_{i,i}}{u_{i,i}} \right)^2 + \sum_{j=1}^{M} \omega_j \left( \frac{\Delta u_{j,j}}{u_{j,j}} \right)^2
\]

\[
\min u_i^f \leq u_{i,i} + \Delta u_{i,i} \leq \max u_i^f \quad i \in \alpha_k
\]

\[
\min u_j^f \leq u_{j,j} + \Delta u_{j,j} \leq \max u_j^f \quad j \in \alpha_i
\]

\[
\Lambda_v = \sum_{i=1}^{N} \frac{x_i}{x_i} + \sum_{j=1}^{M} \frac{y_j}{y_j} + \sum_{k=1}^{L} \frac{z_k}{z_k} + \sum_{l=1}^{P} \frac{w_l}{w_l}
\]

(18)

(19)

(20)

(21)

The names and meanings of variables in the formula are consistent with the model in Section 3.2.

4. Simulation analysis

In this paper, a modified 3-machine 10-node system is used to illustrate the effectiveness of the proposed method. By replacing a high voltage AC transmission line in the original system with a DC line, an AC-DC hybrid transmission system is constructed. The AC/DC system is shown in Figure. 2, in which the rated voltage of the HVDC system is 660 KV and the transmission power is 1100 MW. The operation mode of HVDC system is constant power control on rectifier side and constant arc extinguishing angle control on inverter side. The adjustable range of DC transmission power is [500MW 1200MW], and the adjustable range of arc extinguishing angle is [10° 45°]. Bus 4 and Bus 5 add additional reactive power compensation, 500 MVar and 600 MVar respectively.

4.1. HVDC system participates in voltage control of AC/DC system

In this section, the ability of DC system to participate in voltage control is explained. The control quantity of other AC systems is neglected. The lower limit of voltage constraint is 0.90 p.u., the
voltage amplitude requiring recovery is 0.95 p.u., and the step of voltage adjustment is 0.01. As the load continues to grow, the specific simulation results are shown in Figure 3.

By comparing Figure 3 (a) and Figure 3 (b), it can be seen that the load margin of the system has been significantly improved after considering the participation of DC system in voltage control. As can be seen from Figure 3 (b), with the increase of load, when the lowest voltage amplitude first drops to 0.9p.u., the rectifier side converter and the inverter side converter of the DC system participate in the voltage control start-up, restoring the voltage to the required 0.95p.u. As the load continues to grow, the voltage amplitude will drop to 0.9p.u. for the second time. The HVDC system is involved in voltage control to start again, and the voltage amplitude is worth increasing. However, due to the exhaustion of the control quantity of the HVDC system (the control quantity is restricted to the adjustable limit), the second voltage rise value does not reach the required 0.95p.u., but the voltage level is still improved. Figure 3 (c) and Figure 3 (d) respectively give the DC side power control signal and the inverter side arc extinguishing angle control signal. It can be seen that the DC system effectively participates in the correction of voltage amplitude.

4.2. Coordinated voltage optimal control for AC/DC systems

In this section, the simulation analysis of coordinated participation of AC and DC system in voltage control is given. In addition to the DC system converter control, the generator terminal voltage control and capacitor compensator control are considered.

In the switching process of the filter, the consecutive commutation failure of HVDC transmission lines occurs. In the process of filter removal, the first commutation failure occurred, and the second commutation failure occurred around 200 ms. The corresponding waveforms of DC current and arc extinguishing angle are shown in Figure 4. The terminal voltage of the generator is adjusted to [0.95p.u., 1.05p.u.], and the maximum compensation capacitance of the capacitor is 1.2 times of the initial value. The minimum voltage amplitude of trigger voltage correction control is 0.9p.u., and the voltage amplitude required to recover after control is 1.0p.u. For simplicity, the weights of different control variables are set to 1. The simulation results are shown in Figure 4.
Figure 4 (a) ~ (d) gives the control signals of different control variables of AC/DC system. Through the combined action of control variables of AC/DC system, the voltage amplitude of the system deserves to be corrected effectively to ensure that the voltage can operate within the safety constraints. Figure 4 (e) shows the voltage trajectory of the load bus as the load increases. When the system control resources are exhausted, the voltage loses stability. Based on the simulation analysis of Figure 5, it is verified again that the proposed coordinated voltage control method for AC/DC system can coordinate the control variables of AC/DC system for voltage amplitude correction and improve the voltage stability of the system.

**Figure 4. Simulation results of coordinated voltage optimal control for AC/DC systems.**

5. Conclusion
In this paper, a sensitivity-based coordinated voltage optimization control method for AC/DC hybrid transmission system is proposed. The effectiveness of the proposed control method is illustrated by simulation analysis of an example. The following conclusions are drawn:
1) Through sensitivity analysis of AC/DC system, the effective voltage control quantity can be determined quickly and all the control quantity of the system can be avoided.
2) The control of DC system is flexible and fast, which can effectively participate in voltage safety control and is an important means of voltage safety control.
The coordinated voltage optimization control of AC/DC system can effectively coordinate the control variables of DC system and AC system, and significantly improve the voltage stability of the system.

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