An LCC/VSC Hybrid Structure And Its Coordinated Control In Medium-Voltage DC Distribution System

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Abstract—**In order to reasonably exploit the advantages of line commutated converter (LCC) and voltage source converter (VSC), a coordinated LCC/VSC control strategy applicable to DC distribution network structures is proposed in this paper. In steady-state operation, LCC and VSC perform power distribution according to the set distribution ratio, and LCC can be put into operation or shut down at the right time according to power changes. This power distribution strategy fully exploits the advantages of LCC's large capacity, reduces the pressure on the transmission power of VSCs, and provides a feasible solution for the application of large-capacity LCC in DC distribution networks. Meanwhile, when power fluctuation occurs in the DC distribution network, DC voltage fluctuation spikes can be reduced by VSC/LCC under the action of the virtual direct current generator (VDG) control strategy. The simulation results of MATLAB/SIMULINK verify the feasibility and effectiveness of the method.**

Keywords—DC distribution network, LCC/VSC, voltage fluctuation suppression, coordinated control

I. INTRODUCTION

In recent years, DC distribution networks have received a lot of academic attention due to a series of advantages over AC distribution networks. Voltage source converter (VSC) is widely used as a grid-connected converters for DC voltage control in existing medium voltage DC distribution network projects, but its high cost and maintenance cost restrict the further development of DC distribution system. Compared with VSC, line commutated converter (LCC) has the advantages of larger capacity, lower cost and operating loss, but also has the disadvantages of limited minimum transmission current and slower response speed. The introduction of LCC into DC distribution network can reduce equipment investment and maintenance cost by replacing VSC to take up part of the transmitted power.

In order to reasonably exploit the advantages of LCC and VSC, a variety of hybrid DC transmission systems with different topologies have been proposed. The topologies proposed in [1]–[4] can use VSC to provide dynamic reactive power compensation for LCC, stabilize the ac bus voltage, and reduce the probability of commutation failure of LCC. In [5], [6], an end-to-end hybrid DC transmission topology is proposed, in this topology LCC and VSC are located at the two terminals of the system, which perform rectifier or inverter functions respectively. This topology can be used for the purpose of preventing commutation failed and reducing costs. However, both rectifier side and inverter side exist in the above topologies, and they all focus on end-to-end stable power transmission as the main control purpose. Unlike DC transmission, the DC side of the DC distribution network is usually connected to a large number of loads and distributed power sources, and its power flow changes rapidly and frequently, so how to coordinate and control each converter to maintain the DC side power balance effectively and reduce the DC side voltage fluctuation becomes an important control objective. At the same time, compared with VSC, LCC has the limitation that it cannot operate under light load conditions because its DC side current will be intermittent during light load operation. Obviously, the existing control strategy will no longer be applicable after introducing LCC into DC distribution network, and how to coordinate the operation of LCC and VSC in DC distribution network becomes an urgent problem to be solved.

Due to the small value of the equivalent shunt capacitance of the actual DC distribution network in general, the inertia of the DC system is small compared with the AC system, and the voltage fluctuation is larger when the power fluctuation occurs on the DC side. The change of loads in the DC system and the random fluctuation of power output from distributed generations (DGs) such as photovoltaic and wind power can have a large impact on the DC voltage and even endanger the safe operation of the DC system [7]. Meanwhile, As the interface between the DC distribution network and the utility grid, grid-connected converters play a significant role in maintaining the dc bus voltage stability [8], [9]. However, the introduction of LCC will reduce the number or capacity of VSC in the DC system, and the dynamic response performance of LCC is poorer than that of VSC, which will make the fluctuation of DC voltage more serious when power imbalance occurs. In order to suppress voltage fluctuation by grid-connected converters, a virtual inertia control strategy for DC systems with grid-connected converters similar to virtual synchronous machines (VSMs) is proposed to improve the inertia of DC systems and suppress the fluctuation of DC bus voltage in [10]. To suppress voltage fluctuations, a variable droop coefficient control strategy based on BGCs is proposed, which adaptively changes the droop coefficient when power fluctuations occur in [11]. In [12], a new output voltage feedforward compensation method for improvement of transient state response is proposed, but this method is only applicable to Space Vector Pulse Width Modulation (SVPWM).

In this paper, a LCC/VSC coordinated control strategy suitable for medium voltage DC distribution network structure is proposed. Firstly, for the active power control in the steady-

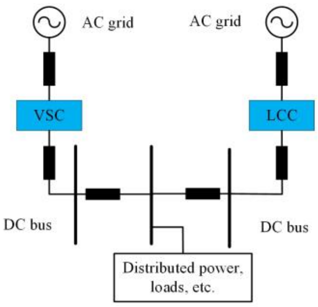

Fig. 1. Schematic diagram of LCC/VSC DC distribution network structure

state operation of the system, a power distribution strategy for LCC and VSC is proposed in this paper. When the transmitted power is small and the power flows in the reverse direction, LCC will be shut down and VSC takes up all the transmitted power; when the transmitted power is large, LCC will be put into operation and takes up most of the power; while the reactive power control of both can be transplanted using the existing mature control strategy of LCC/VSC hybrid DC transmission system. The proposed power distribution strategy fully exploits the advantages of LCC's large capacity and reduces the pressure of VSC to transmit power, providing a feasible solution for the application of large-capacity LCC to DC distribution networks. Second, When power fluctuation occurs in the DC distribution network, DC voltage fluctuation spikes can be reduced by VSC/LCC under the action of the VDG control strategy. Finally, the simulation results of MATLAB/SIMULINK are used to verify the feasibility and effectiveness of the proposed method. This paper provides a new method for the application of LCC to DC distribution networks in DC distribution networks.

II. VSC AND LCC POWER DISTRIBUTION STRATEGY FOR STEADY-STATE OPERATION OF DC DISTRIBUTION NETWORK BASED ON LCC/VSC

In this paper, a power distribution strategy is proposed for a two-terminal DC distribution network based on LCC/VSC. The two-terminal DC distribution network topology based on LCC/VSC is shown in Fig. 1.

Based on the above analysis, and in order to make full use of the advantages of LCC's large capacity, the LCC/VSC power distribution restrictions can be obtained: LCC should be shut down when the system operate under light load conditions because its DC side current will be intermittent and the trigger angle will be larger during light load operation, which will lead to higher harmonic component of the AC and DC side and higher reactive power consumed by the converter, making its operation performance deteriorates. When the system operate under heavy load conditions, LCC should be put into operation before VSC reaches the power transfer limit. LCC should reach power transfer limit before VSC when LCC is in operation to ensure that VSC always has a certain capacity for voltage control before LCC reaches the power transfer limit.

Assume that the rated voltage of DC side is U_{dcN}, and the active power they transmit to DC distribution network are P_{VSC} and P_{LCC}, P_{VSC_max} and P_{LCC_max} denote the maximum value of power that VSC and LCC can transmit to DC system respectively. The maximum value of DC side current of LCC is I_{LCC_max}. The DC system consumes power is P_L, i.e., P_L = P_{VSC} + P_{LCC}, and defines the load factor of DC system as $\beta_L = \dfrac{P_L}{P_{VSC\_\max} + P_{LCC\_\max}}$.

Based on the above analysis, when P_L is large, LCC should be put into operation and take up larger transmission power; and when P_L gradually decreases, LCC should also reduce the transmission power simultaneously. When P_L further decreases so that the system operate under light load conditions, LCC should be shut down. Assume that the DC side load current of LCC is $a \cdot I_{LCC\_\max}$ when it is critically shut down, where $10\% \le a < 1$, the power transmitted by LCC to the DC distribution network $P_{LCC} = U_{dcN} \cdot a \cdot I_{LCC\_\max} = a \cdot P_{LCC\_\max}$. At this time the DC system consumes power $P_L = p_0$, and the corresponding DC system load factor $\beta_L = \dfrac{p_0}{P_{VSC\_\max} + P_{LCC\_\max}} = m$, $P_{VSC} = p_0 - P_{LCC} = m \cdot P_{VSC\_\max} + (m-a) \cdot P_{LCC\_\max}$. That is, when LCC is critically shut down, the system operation state satisfies (1).

$$\begin{cases} P_{LCC} = a \cdot P_{LCC\_\max} \\ P_{VSC} = m \cdot P_{VSC\_\max} + (m-a) \cdot P_{LCC\_\max} \\ \beta_L = \dfrac{p_0}{P_{LCC\_\max} + P_{VSC\_\max}} = m \end{cases} \tag{1}$$

Then the load power distribution ratio of LCC and VSC at this time is

$$\frac{P_{LCC}}{P_{VSC}} = \frac{a \cdot P_{LCC\_\max}}{m \cdot P_{VSC\_\max} + (m-a) \cdot P_{LCC\_\max}} \tag{2}$$

That is, when LCC is in operation and the transmission power limit has not been reached, the power distribution relationship between LCC and VSC should satisfy (2), which ensures that the system should satisfy (1) when LCC starts to be shut down.

In order to make the system operate in a reasonable state, the total transmission power should be greater than the LCC transmission power at the time of LCC critical shutdown, i.e.

$$(P_{LCC\_\max} + P_{VSC\_\max}) \cdot m > P_{LCC\_\max} \cdot a \tag{3}$$

When the system operate under light load conditions, β_L is less than $\dfrac{p_0}{P_{LCC\_\max} + P_{VSC\_\max}}$ at this time. According to the above analysis, LCC has been shut down, and as P_L increases, the transmission power taken up by VSC also increases. In order to ensure that the VSC always has certain capacity for voltage control before the LCC reaches the power transmission limit, the LCC should be put into operation before the VSC reaches the power transmission limit. Assuming that at the critical start-up time of the LCC, the load rate of VSC $\dfrac{P_{VSC}}{P_{VSC\_\max}} = b$ and the load rate of DC system $\beta_L = \dfrac{b \cdot P_{VSC\_\max}}{P_{LCC\_\max} + P_{VSC\_\max}} = n$. When $\beta_L \ge n$, the LCC should be put into operation in time if it is out of operation in the

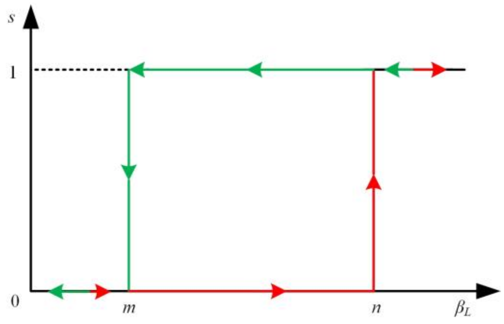

Fig. 2. LCC state switching logic diagram

process of the system from light load to heavy load conditions. That is, when the LCC is put into operation critically, the system operation state satisfies (4).

$$\begin{cases} P_{VSC} = b\cdot P_{VSC\_\max} \\ \beta_L = \dfrac{b\cdot P_{VSC\_\max}}{P_{VSC\_\max}+P_{LCC\_\max}} = n \end{cases} \tag{4}$$

After LCC is put into operation, the power is distributed between LCC and VSC according to (2). The value of *b* determines the capacity margin reserved by VSC for voltage control, (1-*b*)P_{VSC_max} should be greater than the maximum possible fluctuating power of the DC system.

Similarly, in order to ensure that VSC always leaves a certain capacity for voltage control before the LCC reaches the power transfer limit, LCC should reach the power transfer limit before VSC when the system operate under heavy load conditions. And at the moment when the LCC critically reaches the power transfer limit, the loading rate of the VSC should satisfy $\dfrac{P_{VSC}}{P_{VSC\_\max}} \le b$, then the system operation state satisfies (5)

$$\begin{cases} P_{LCC} = P_{LCC\_\max} \\ P_{VSC} \le b\cdot P_{VSC\_\max} \end{cases} \tag{5}$$

From the above analysis, it can be seen that when $\beta_L \le m = \dfrac{p_0}{P_{VSC\_\max}+P_{LCC\_\max}}$, at this time $\dfrac{P_{LCC}}{P_{LCC\_\max}} \le a$, LCC should be shut down immediately if it is in operation. When $\dfrac{P_{VSC}}{P_{VSC\_\max}} \ge b$, at this time $\beta_L \ge n = \dfrac{b\cdot P_{VSC\_\max}}{P_{VSC\_\max}+P_{LCC\_\max}}$, LCC should be started and put into operation immediately if it is out of operation. If $s = 0$ means LCC is out of operation and $s = 1$ means LCC is in operation, then

$$\begin{cases} s=0, & \beta_L \le m \\ s=1, & \beta_L \ge n \end{cases} \tag{6}$$

The relationship between *s* and β_{load} can be shown in Fig. 2.

In summary, during normal operation of the system, the operating state of LCC is adjusted in time according to the change ofβ_L. Moreover, when LCC is in operation, the current reference value of LCC is dynamically adjusted so that the load distribution between LCC and VSC satisfies (2), and LCC is no longer involved in the power distribution of newly added load when the output power reaches the power transfer limit.

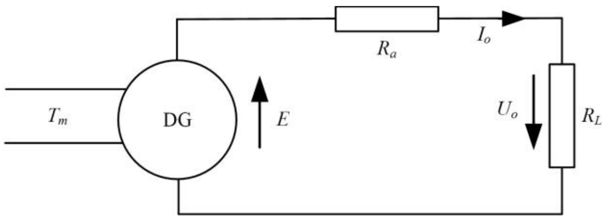

Fig. 3. Basic input-output model of a DC generator

III. VOLTAGE FLUCTUATION SUPPRESSION CONTROL STRATEGY FOR DC DISTRIBUTION NETWORK

Due to the small value of the equivalent shunt capacitance of the actual DC distribution network in general, the inertia of the DC system is small compared with the AC system, and the voltage fluctuation is larger when the power fluctuation occurs on the DC side, which has a greater impact on the voltage quality. The VDG control strategy allows power electronics to simulate the rotational inertia and damping characteristics of a rotating motor, making it equivalent to a DC generator in terms of external characteristics, thus coping with sudden voltage changes caused by disturbances to improve the stability of the system voltage. In order to make the converter have similar regulating characteristics with DC generator, this section will lead the principle of VDG control strategy from the mathematical model of DC generator, and design the control strategy of LCC and VSC based on VDG control, so that VSC and LCC have similar output external characteristics with DC generator, and increase the inertia of the DC grid, so as to better stabilize the DC bus voltage.

The basic equations of DC generator are mainly composed of two parts: mechanical equations and electromagnetic equations. Fig. 3 shows the basic model of DC generator input and output, where T_m is the input mechanical torque of DC generator, E is the armature electromotive force of DC generator, R_a , I_o , U_o are the total resistance, armature current and output voltage of generator armature circuit respectively; R_L is the equivalent load.

As shown in Fig. 3, the DC generator rotor generates armature electromotive force E under the input mechanical torque T_m , which is used to supply power to the load through the line. The generator generates an electromagnetic torque T_e while outputting electrical energy, and the motion of the generator rotor is determined by both the mechanical torque T_m and the electromagnetic torque T_e .

The following is an analysis of the mechanical and electromagnetic equations of the DC generator.

1) Mechanical equations

$$\begin{cases} J\dfrac{\mathrm{d}\omega}{dt} = T_m - T_e - D\left(\omega-\omega_0\right) \\ T_e = \dfrac{P_e}{\omega} \end{cases} \tag{7}$$

where J and D are the generator rotational inertia and damping coefficient, respectively; ω and ω_0 are the actual

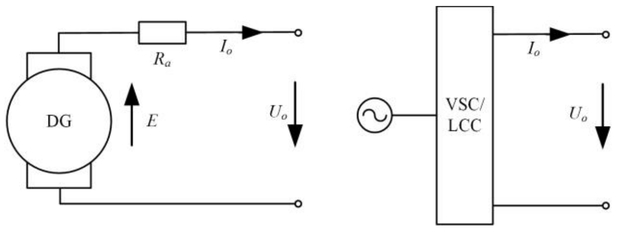

Fig. 4. The VDG model of VSC/LCC

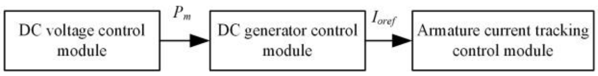

Fig. 5. The VDG control strategy logic diagram

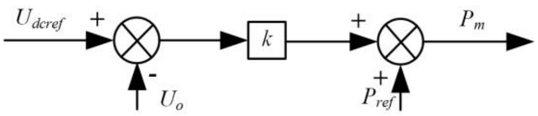

Fig. 6. The droop control diagram

and rated rotor angular velocity, respectively; P_e is the electromagnetic power corresponding to T_e.

2) Electromagnetic equations

$$\begin{cases} U_o = E - I_o R_a \\ E = \mathrm{C}_T \Phi \omega \end{cases} \tag{8}$$

where C_T and Φ are the torque coefficient and flux per pole, respectively.

When the mechanical power of the DC generator changes suddenly, the mechanical angular velocity ω of the DC generator changes slowly due to the rotational inertia coefficient J and the damping coefficient D. As known from (8), when ω changes slowly, the armature electromotive force E of the DC generator changes smoothly instead of abruptly, showing the damping and inertia characteristics of the DC generator.

The VDG model of VSC and LCC is shown in Fig. 4. By equating the DC side output of VSC and LCC as the armature output of DC generator, and by introducing the mechanical and electromagnetic equations of DC generator into the control strategy of VSC and LCC, the damping and inertia characteristics of DC generator can be simulated by VSC and LCC, thus realizing the VDG control of VSC and LCC.

From Fig. 5, it can be seen that the VDG consists of three modules: the DC voltage control module, the DC generator control module and the armature current tracking control module, respectively. These three modules are analyzed below.

1) DC voltage control module

This module adopts droop control and its U - P characteristics are shown in Fig. 6. The relationship between active power and DC voltage in the steady-state operation of the converter can be expressed as

$$P_m = P_{ref} + k(U_{dcref} - U_o) \tag{9}$$

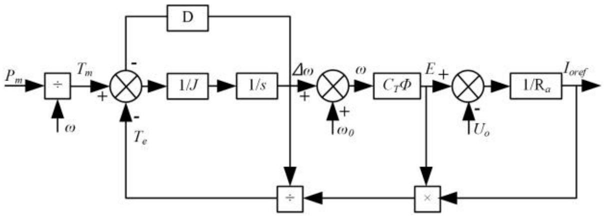

Fig. 7. DC generator control module schematic

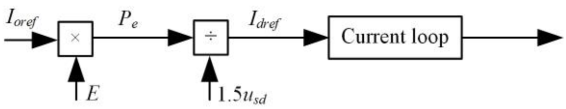

Fig. 8. Armature current tracking control module of VSC

where U_o and U_{dcref} are the actual and rated values of the converter output voltage, P_m and P_{ref} are the reference and rated values of the converter output power, the power direction is positive to the DC distribution network, and k is the droop coefficient.

2) DC generator control module

The current mechanical torque T_m of the VDG can be derived from the mechanical power P_m, and the reference value of armature current I_{oref} can be obtained by combining the mechanical equations and electromagnetic equations of the DC generator.

3) Armature current tracking control module

The current reference value I_{aref} can be obtained from the DC generator control module. For the VSC, I_{aref} is converted to the current loop reference value for controlling the VSC, and the reference value is used to regulate the output current of the converter, as shown in Fig. 8, where P_e is the electromagnetic power, u_{sd} is the grid-side voltage d axis components. For LCC, I_{aref} can be used directly as the reference value for the LCC current loop.

Through the above analysis, the VDG control strategy can make the VSC and LCC simulate the rotational inertia and damping characteristics possessed by the DC generator, which can effectively improve the inertia of the system.

IV. SIMULATION

In order to validate the control strategy proposed in this paper, a simulation system in Matlab/Simulink based on Fig. 1 is built. To simulate the power fluctuations caused by load and distributed generation, the voltage DC bus loads and converters other than VSC and LCC are simulated with equivalent resistance. Among them, VSC adopts modular multilevel converter (MMC). $P_{LCC\_\max} = P_{VSC\_\max} = 10\mathrm{MW}$, $U_{dcN} = 20\mathrm{kV}$.

The system is initially operated with an equivalent load power 10 MW. Load power of 2 MW is added at t = 4.5s and shed at t = 16.5s. Droop control strategy is adopted on LCC and VSC, The comparative simulation waveforms of VSC/LCC under two control strategies: conventional droop

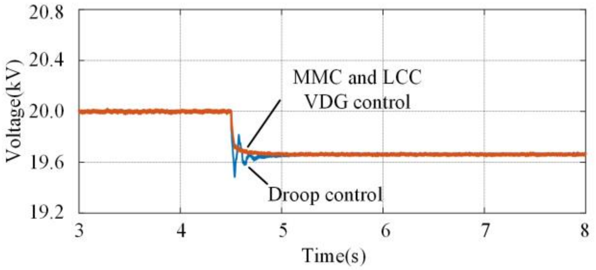

Fig. 9. DC bus voltage waveform when the load power suddenly increases

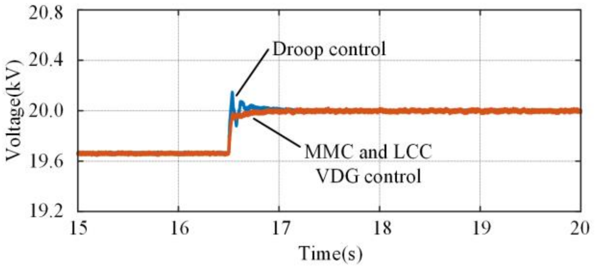

Fig. 10. DC bus voltage waveform when the load power suddenly decreases

control strategy and VDG, are shown in Fig. 9 and Fig. 10.

Compared with the conventional droop control, VSC and LCC VDG control strategy has less voltage fluctuation and higher power quality under the same load variation. The simulation results verify the superiority of the proposed control strategy.

V. CONCLUSION

In order to exploit the advantages of LCC, LCC is introduced into the distribution network and a coordinated control strategy of VSC/LCC applicable to DC distribution network is proposed in this paper. LCC takes up the corresponding power transmission when in operation and can be put into operation or shut down timely during the whole period. When power fluctuation occurs in DC distribution network, VSC and LCC VDG control strategy has less voltage fluctuation and higher power quality under the same load variation compared with the conventional droop control. This paper provides a new method for the application of LCC to DC distribution networks and the solution of voltage fluctuations in DC distribution networks.

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