International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 11 Issue 12, December-2022, Impact Factor: 7.957

Synchronization of an LCC/VSC Hybrid Structure in a Medium-Voltage DC Distribution System

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ABSTRACT

In this paper, a coordinated LCC/VSC control method applicable to DC distribution network architectures is given in order to reasonably leverage the benefits of line commutated converter (LCC) and voltage source converter (VSC). In steady-state operation, LCC and VSC distribute power in accordance with the predetermined distribution ratio, and LCC can be turned on or off at the appropriate moment in response to power variations. This power distribution method makes the most of the huge capacity of LCCs, eases the burden on VSC transmission power, and offers a workable option for applying big-capacity LCC in DC distribution networks.

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

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INTRODUCTION

Due to a number of benefits over AC distribution networks, DC distribution networks have attracted a lot of scholarly research in recent years. The widespread use of voltage source converters (VSC) as grid-connected converters for DC voltage management in current medium voltage DC distribution network projects limits the further expansion of the DC distribution system due to their high cost and maintenance requirements. Line commutated converters (LCC) have higher capacities, lower costs, and operating losses than VSC, but they also have a lower minimum transmission current and a slower response time.

By substituting LCC for VSC to absorb some of the transmitted power, the introduction of LCC into the DC distribution network can lower equipment investment and maintenance costs.

A number of hybrid DC transmission systems with various topologies have been developed in order to effectively utilise the benefits of LCC and VSC. The topologies suggested in [1]–[4] can leverage VSC to lower the likelihood of LCC commutation failure, stabilise the ac bus voltage, and offer dynamic reactive power compensation for LCC. An end-to-end hybrid DC transmission topology is proposed in [5], [6]. In this topology, LCC and VSC are situated at the system's two terminals and serve as rectifiers or inverters, respectively. The goal of using this architecture is to prevent unsuccessful commutations and cut costs. However, both rectifier side and inverter side exist in the above topologies, and they all focus on end-to-end stable Transmission of power is the primary control objective. The DC side of the DC distribution network, in contrast to DC transmission, is typically connected to a large number of loads and distributed power sources, and its power flow changes quickly and frequently. As a result, it becomes crucial to coordinate and control each converter in order to maintain the DC side power balance and lessen the DC side voltage fluctuation. However, in contrast to VSC, LCC has the drawback of being unable to operate under light load situations due to the intermittent nature of its DC side current. After adding LCC to the DC distribution network, the present control method will obviously no longer be appropriate. 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 feed forward 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- state operation of the system, a power distribution strategy for LCC and VSC is proposed in this paper.

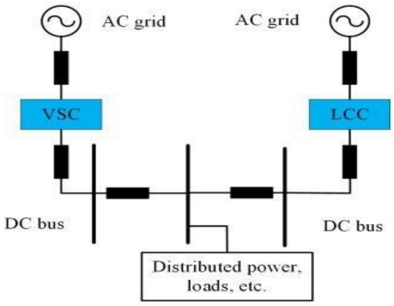


Fig. 1. Schematic diagram of LCC/VSC DC distribution network structure

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.

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 $UdcN$, and the active power they transmit to DC distribution network are $PVSC$ and $PLCC$, $PVSC\_max$ and $PLCC\_max$ 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 $ILCC\_max$. The DC system consumes power is PL, i.e., $PL = PVSC + PLCC$, *and defines the load factor of DC system as*

$$\beta_L = \frac{P_L}{P_{VSC\_max} + P_{LCC\_max}} .$$

Based on the above analysis, when PL is large, LCC should be put into operation and take up larger transmission power; and when PL gradually decreases, LCC should also reduce the transmission power simultaneously. When PL 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 $a\ ILCC\_max$ when it is critically shut down, where $10\% \le a < 1$, the power transmitted by

LCC to the DC distribution network PLCC= UdcN a □ ILCC _ max □ a □ PLCC _ max . At this time the DC system consumes power PL = p0.That is, when LCC is critically shut down, the system operation state satisfies (1).

$$\begin{cases} P_{LCC} = a \cdot P_{LCC\ max} \\ \beta_L = \dfrac{\quad P_{VSC} \quad P_{VSC\_max} \quad P_{LCC\_max}}{P_{LCC\_max} + P_{VSC\_max}} = m \end{cases}$$

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

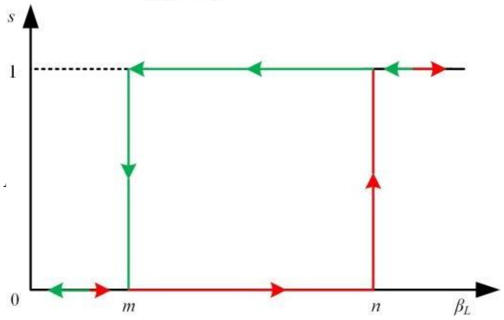
$$\frac{P_{LCC}}{P_{VSC}} = \frac{a \cdot P_{LCC\_max}}{m \cdot P_{VSC\_max} + (m-a) \cdot P_{LCC\_max}} \qquad (2)$$

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.

$$(P_{LCC\_max} + P_{VSC\_max}) \cdot m > P_{LCC\_max} \cdot a \qquad (3)$$

LCC has been shut down, and as *PL* 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

$$\frac{P_{VSC}}{P_{VSC\_max}} = b$$



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).

$$\begin{cases} P_{VSC} = b \cdot P_{VSC\_max} \\ \beta_L = \dfrac{b \cdot P_{VSC\_max}}{P_{VSC\_max} \qquad P_{LCC\ max}} = n \end{cases} \qquad (4)$$

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*)*PVSC_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 then the system operation state satisfies (5)

$$\begin{cases} P_{LCC} = P_{LCC\_max} \\ P_{VSC} \le b \cdot P_{v} \end{cases} \qquad (5)$$

$$\beta_L \le m = \frac{p_0}{P_{VSC\_max}+P_{LCC\_max}}, \qquad \frac{P_{LCC}}{P_{LCC\_max}} < a$$

From the above analysis, it can be seen that when at

this time LCC should be shut down immediately if it is in operation. 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

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

In summary, during normal operation of the system, the operating state of LCC is adjusted in time according to the change of βL. 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.

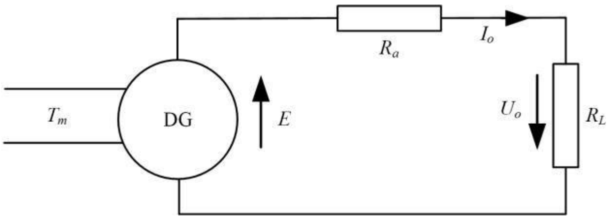


Fig. 2. Basic input-output model of a DC generator

VOLTAGE FLUCTUATION SUPPRESSIONCONTROL 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 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 Tm , which is used to supply power to the load through the line. The generator generates an electromagnetic torque Te while outputting electrical energy, and the motion of the generator rotor is determined by both the mechanical torque Tm and the electromagnetic torque Te and rated rotor angular velocity, respectively; P_e is the electromagnetic power corresponding to T_e .

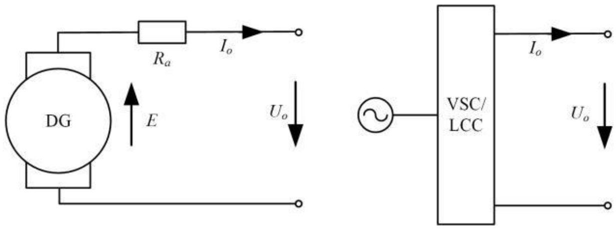


Fig. 4. The VDG model of VSC/LCC

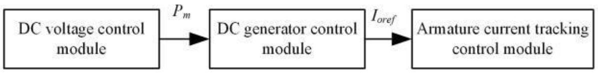


Fig. 5. The VDG control strategy logic diagram

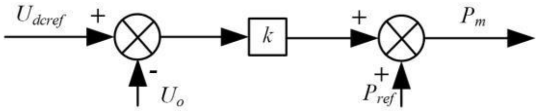


Fig. 6. The droop control diagram

Electromagnetic equations

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. Byequating 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.

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 ofthe converter can be expressed as

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

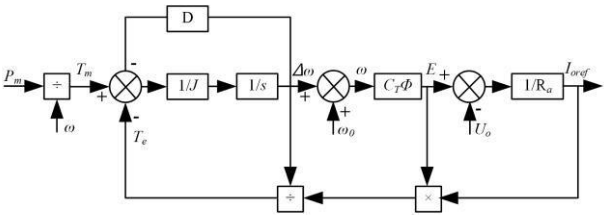


Fig. 7. DC generator control module schematic

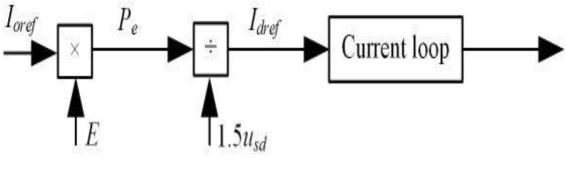


Fig. 8. Armature current tracking control module of VSC

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.

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.

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). $P_{LCC\_\max} = P_{VSC\_\max}$ □ 10MW U_{dcN} □ 20kV .

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

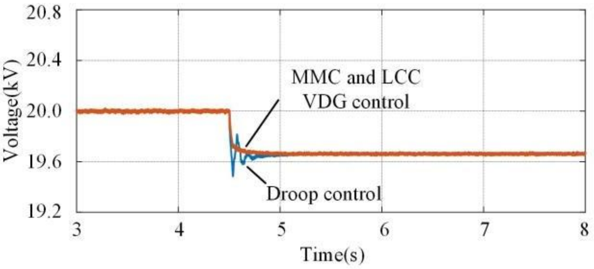


Fig. 9. DC bus voltage waveform when the load power suddenly increases

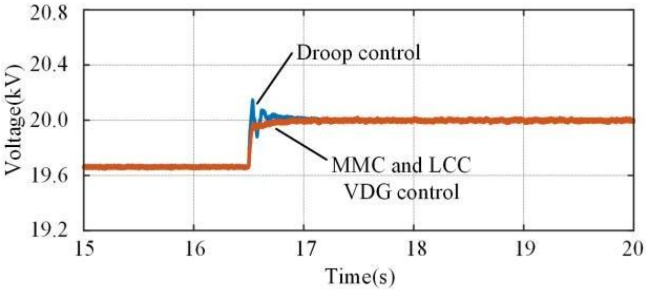


Fig. 10. DC bus voltage waveform when the load power suddenly decreases Control strategy and VDG, are shown in Fig. 4 and Fig. 5.

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.

CONCLUSION

LCC is incorporated into the distribution network in order to take use of its benefits, and this research suggests a coordinated VSC/LCC control technique that may be used with DC distribution networks. When in use, LCC takes up the appropriate power transfer and can be started or stopped at any point throughout the duration. Compared to the standard droop control, the VSC and LCC VDG control technique has improved power quality and reduced voltage fluctuation when power fluctuation occurs in a DC distribution network. In order to apply LCC to DC distribution networks and address voltage fluctuations there, a new technique is presented in this research.

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