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Modeling and simulation of control strategy for voltage source converter multi-terminal DC system

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Abstract

An improved strategy for controlling DC voltage droop is proposed to solve the problems of conventional DC voltage droop control strategy, such as the received power of converter stations is distributed according to fixed proportion, the power variation amplitude is large, the power regulation ability is easy to lose when reaching the upper limit, and there is obvious voltage deviation. A three-terminal VSC-MTDC system model including wind farm was constructed by Matlab/Simulink. According to different conditions of power fluctuation caused by wind power output variation, simulation and analysis of VSC active power and DC voltage variation were carried out. Simulation results showed that the improved strategy for controlling DC voltage droop proposed in this paper made the converter station retain more power regulation margin when the converter station absorbed more active power, and could prevent the converter station from losing its power regulation ability when the power reached the upper limit, and realize reasonable power distribution among converter stations. Meanwhile, the proposed control strategy could maintain DC voltage constant, which verified the feasibility of its application in wind power grid-connected flexible DC transmission system.

Keywords: improved DC voltage droop control, wind farm, VSC-MTDC, VSC.

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1. Introduction

In recent years, centering on the problems of energy shortage and environmental pollution, continuously optimizing and adjusting the energy structure and building a new power system with new energy sources such as wind power, photovoltaic power and hydropower as the main body have become an inevitable trend for countries around the world to achieve sustainable development. As a form of clean energy with advanced technology, wind power has entered a new period of large-scale and steady development in China. However, due to its randomness and volatility, it causes deterioration of power quality and poses a threat to power safety [1]. The voltage source converter multi-terminal DC system (VSC-MTDC) is based on the existing transmission network and consists of at least three voltage source converters (VSC) and their connected lines [2-3]. The advantage of it is that it has low transmission costs, high energy utilization and operation reliability, and flexible power flow control [4]. It makes up for the disadvantage that the two-terminal flexible DC transmission system needs to be withdrawn from operation due to the failure of one converter station or line [5]. But the control strategy of VSC-MTDC also becomes more complicated. In VSC-MTDC system, the fluctuation of DC voltage directly affects the stable operation of the system. Therefore, the DC voltage is a reflection of the active power balance, and its control capacity is a crucial indicator of system stability [6].

The VSC-MTDC system's main control strategy presently is DC voltage margin control, master-slave control, and DC voltage droop control. DC voltage droop control can utilize the power regulation capability of multiple converter stations

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without inter-station communication and has higher reliability, becoming one of the most widely used control strategies in VSC-MTDC systems. And a large number of references have been studied on it. The disadvantages of DC voltage droop control were overcome by proposing a general control strategy based on voltage droop control in reference [7]. By adjusting droop coefficient, this method could be applied to conventional voltage droop control, constant active power control and constant DC voltage control. A control strategy of automatic droop coefficient adjustment was proposed in reference [8], which solved the problem that the power margin of a single converter station was insufficient and affected the power allocation of the system. The reference [9] applied voltage margin control to DC voltage droop control, which made VSC-MTDC stable and adaptable to large unbalanced power. Reference [10] added a constant reference value on the basis of DC voltage droop control, and realized the goal of real-time adjustment of DC voltage with power change. A dual control strategy combining DC voltage and frequency droop was proposed in reference [11]. This method integrated the advantages of frequency control and DC voltage control, but it had the disadvantage that it was easy to lead to system deterioration when DC voltage deviation was large. An improved strategy for controlling DC voltage droop was proposed in reference [12], which could rebalance the power after a converter station was out of operation and make the system reach stable state again. An adaptive control strategy for DC voltage deviation was proposed in reference [13], which improved the stability of DC voltage effectively, but the detailed study on parameter selection was lacking. Although DC voltage droop control has many advantages in VSC-MTDC system application, it still has some disadvantages such as voltage regulation and power distribution characteristics are affected by droop coefficient, active power transmission accuracy is insufficient and DC voltage steady-state characteristics are poor[14].

In view of this, this paper proposes an improved strategy for controlling DC voltage droop. Based on the conventional DC voltage droop control method, the droop coefficient can automatically track the power margin value of converter station by constructing power margin coefficient H_P. DC voltage influence weight μ is introduced, and DC voltage deviation is used to change droop coefficient operating point, so as to ensure DC voltage can be maintained in a reasonable range when H_P is too small. When converter stations absorb more active power, they reserve more power regulation margin to prevent them from losing power regulation ability due to power reaching upper limit, and realize reasonable power distribution among converter stations. Finally, a three-terminal VSC-MTDC system model including wind farm is constructed by Matlab/Simulink. Simulation results under different conditions of wind farm power fluctuation showed that the improved strategy for controlling DC voltage droop could maintain DC voltage constant under different conditions, and verify the feasibility of the proposed control strategy in the application of wind farm grid-connected flexible DC transmission system.

2. Principle and mathematical model of flexible HVDC technology

2.1 Technical Principle of Flexible HVDC Technology

According to the different operation modes, flexible DC transmission system can be divided into two types: Voltage Source Converter High Voltage Direct Current (VSC-HVDC) system and multi-terminal VSC-MTDC system. Among them, VSC-HVDC system is widely used in engineering practice because of its simple control structure, but it has some defects such as poor flexibility and insufficient stability. VSC-MTDC system is mainly developed from VSC-HVDC system, its power flow control is more flexible, can realize the interconnection of multiple asynchronous power grids, and solves the problem that one converter station of VSC-HVDC system is shut down due to fault, which leads to the whole system out of operation. But the system structure and its control strategy have also become more complex. The operation principle of VSC-MTDC system is explored through the analysis of VSC-HVDC system.

VSC-HVDC system is mainly composed of voltage source converter (VSC), connecting transformer, converter reactor, AC filter, DC capacitor and AC bus, and its principle structure diagram is shown in Figure 1.

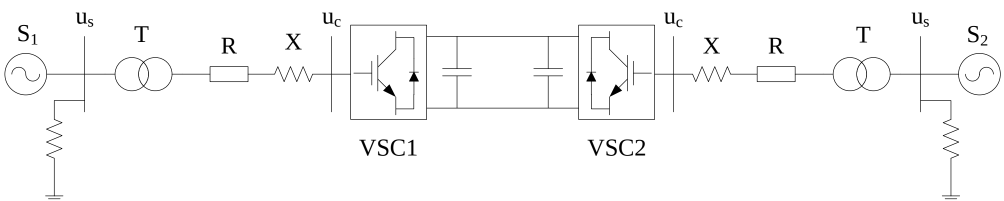


Figure 1. Schematic diagram of VSC-HVDC system

In flexible DC transmission system, power can flow bidirectionally, that is, converter can be used as rectifier station to transmit power received by AC system through DC line, and can also be used as inverter station to transmit power from DC side to AC side. The VSC fundamental equivalent circuit is shown in Figure 2.

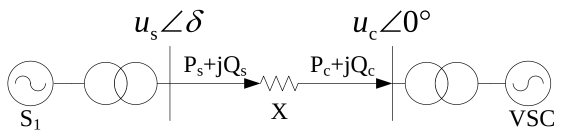


Figure 2. VSC Fundamental Equivalent Circuit

In the figure, X represents the reactance between converter and AC equivalent system, including the reactance of connecting reactor and connecting transformer. u_s and u_c represent AC system equivalent fundamental voltage and converter AC side fundamental voltage respectively. The active and reactive power input to the converter by the AC system is represented by P_s and Q_s. The AC side of the converter has P_c and Q_c representing the active and reactive power. According to the equivalent circuit diagram of the fundamental wave of the converter, the relationship between the active power, reactive power and voltage of the converter can be obtained as follows:

$$P_s = \frac{u_s u_c}{X}\sin\delta \tag{1}$$

$$Q_s = \frac{u_s(u_s - u_c\cos\delta)}{X} \tag{2}$$

$$u_c = \frac{\mu M}{\sqrt{2}} u_{dc} \tag{3}$$

Where, μ represents the DC voltage utilization ratio, u_{dc} represents the DC voltage rating value, M represents the modulation ratio of the PWM modulation wave, and δ represents the phase difference between the AC system fundamental wave voltage u_s and the converter AC side fundamental wave voltage u_c.

When VSC is modulated, active power can be controlled by adjusting the phase angle δ of PWM modulation wave, and reactive power can be controlled by adjusting modulation ratio M [15]. When δ>0, i.e. u_s leads u_c, the converter works in rectification state, active power being transferred from AC to DC side.; when δ<0, i.e. u_s lags u_c, the converter works in inversion state, active power being transferred from DC to AC side. When $u_s - u_c\cos\delta > 0$, the converter consumes reactive power; when $u_s - u_c\cos\delta < 0$, the converter transmits reactive power to the AC side [16].

2.2 Mathematical Model of Flexible DC Transmission System

Voltage source converters (VSC) mainly include three forms: two-level VSC, three-level VSC, and modular multilevel converters (MMC). Among them, two-level VSC has simple structure and mature technology, which is widely used in flexible DC transmission projects. Its basic principle is shown in Figure 3.

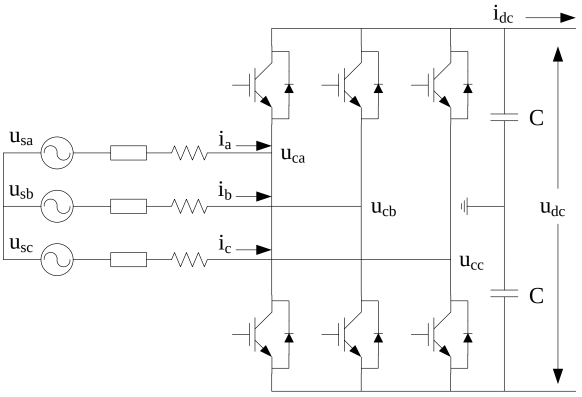


Figure 3. Basic principle diagram of VSC

In the figure, the AC side bus's three-phase voltage is represented by u_{sa}, u_{sb} and u_{sc}. Three-phase current on the AC side is represented by i_a, i_b and i_c. The input voltage of the AC side of the converter is represented by u_{ca}, u_{cb} and u_{cc}. The DC side voltage and DC line current of VSC are represented by u_{dc} and i_{dc}. The equivalent resistance and reactance of VSC are represented by R and L respectively. The converter's DC capacitance is represented by C. In a three-phase stationary coordinate system, the mathematical model of VSC can be described as [3, 17]:

$$L\frac{d}{dt}\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} - \begin{bmatrix} u_{ca} \\ u_{cb} \\ u_{cc} \end{bmatrix} - R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4}$$

The mathematical model of VSC in the d-q rotating coordinate system is obtained through Park transformation on equation (4), as described below:

$$L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} u_{sd} \\ u_{sd} \\ u_{s0} \end{bmatrix} - \begin{bmatrix} u_{cd} \\ u_{cq} \\ u_{c0} \end{bmatrix} - R\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} - LP\frac{dp^{-1}}{dt}\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{5}$$

Simplifying equation (5), in a d-Q synchronous rotating coordinate system, the mathematical model of a flexible DC transmission system can be obtained using the following methods:

$$\begin{cases} L\dfrac{di_d}{dt} = u_{sd} - u_{cd} - Ri_d + \omega L i_q \\ L\dfrac{di_q}{dt} = u_{sq} - u_{cq} - Ri_q - \omega L i_d \end{cases} \tag{6}$$

Where, u_{sd} and u_{sq} represent d and q axis voltage components at the bus of AC system respectively, and u_{cd} and u_{cq} represent d and q axis voltage components at AC side of VCS respectively. A variant of equation (6) yields:

$$\begin{cases} u_{cd} = u_{sd} - \mathrm{L}\dfrac{di_d}{dt} - Ri_d + \omega L i_q \\ u_{cq} = u_{sq} - \mathrm{L}\dfrac{di_q}{dt} - Ri_q - \omega L i_d \end{cases} \tag{7}$$

It can be seen that the AC side voltages u_{cd} and u_{cq} of VSC are not only affected by the AC side voltage and current, but also the d and q axis variables are coupled with each other. By adopting the feed forward double closed-loop decoupling control strategy, the control equations of the controlled voltages u_{cd} and u_{cq} can be obtained as follows:

$$\begin{cases} u_{cd} = u_{sd} + \omega L i_q - \left(K_{pd} + \dfrac{K_{id}}{s}\right)(i_{dref} - i_d) \\ u_{cq} = u_{sq} - \omega L i_d - \left(K_{pq} + \dfrac{K_{iq}}{s}\right)(i_{qref} - i_q) \end{cases} \tag{8}$$

The inner-loop current decoupling controller of the converter was designed according to equation (8), and its structure is shown in Figure 4.

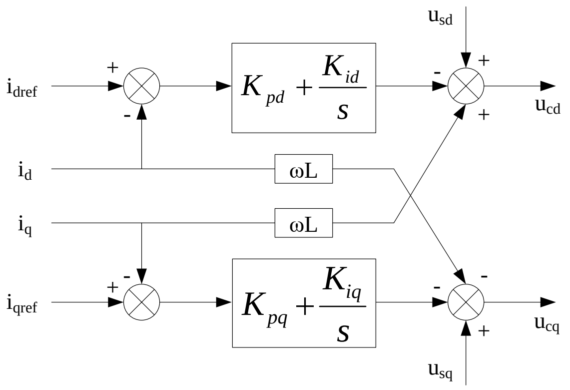


Figure 4. Structure of inner loop decoupling controller

The basic control mode of VSC-MTDC is mainly determined by the voltage outer loop controller. Active control parameters and reactive control parameters are the objectives of voltage source converter outer loop control [18]. Constant DC voltage, constant active power and constant AC system frequency are the main active control parameters. Reactive control parameters mainly include constant AC voltage and constant reactive power.

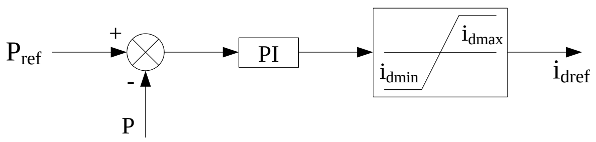
The AC system in a d-q rotating coordinate system has an active power P and a reactive power Q that are both based on the instantaneous reactive power principle.

$$\begin{cases} P = \dfrac{3}{2}(u_d i_d + u_q i_q) \\ Q = \dfrac{3}{2}(u_q i_d - u_d i_q) \end{cases} \tag{9}$$

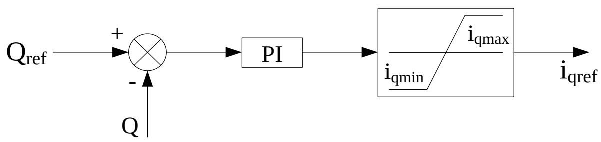
When voltage orientation is adopted, the direction of selection for the d axis is the same as that of the voltage vector, then $u_q = 0$. By giving the reference values P_{ref} and Q_{ref} of active and reactive power, the reference values i_{dref} and i_{qref} output to the current inner loop can be obtained as follows:

$$\begin{cases} i_{dref} = \dfrac{2P_{ref}}{3u_d} \\ i_{qref} = -\dfrac{2Q_{ref}}{3u_d} \end{cases} \tag{10}$$

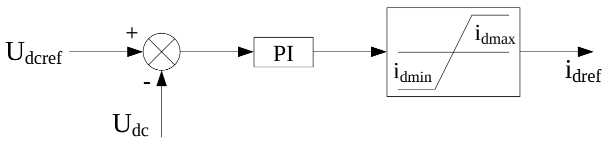
To track the reference values of active power and reactive power, PI proportional-integral control could be introduced, and the constant active power and reactive power control structures were designed accordingly, as shown in Figure 5 (a) and Figure 5 (b) respectively.



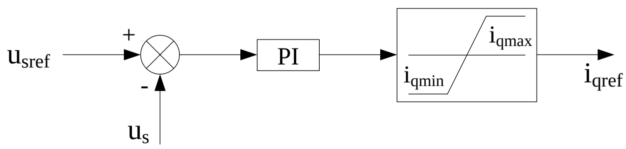
(a) Constant active power control



(b) Constant reactive power control



(c) Constant DC voltage control



(d) Constant AC voltage control

Figure 5. Structure of voltage outer loop controller

To achieve active power balance in the VSC-MTDC transmission system, a constant DC voltage control mode is used by at least one converter station to stabilize DC voltage and balance unbalanced power balance nodes. Neglecting the power loss in the converter station, the power on both sides is equal, that is:

$$P = \frac{3}{2} u_d i_d = P_{dc} = U_{dc} I_{dc} \tag{11}$$

Where, P_{dc}, U_{dc} and I_{dc} represent DC power, DC voltage and DC current on DC side of converter respectively. When the system is in steady state, its DC current I_{dc} is:

$$I_{dc} = \frac{3u_d i_d}{2U_{dc}} \tag{12}$$

It can be seen from Equation (12) that when there is an imbalance in the power on both sides of the converter. adjusting the size of i_d can make the current flow into and out of the DC side capacitor of the converter station for charging and discharging, so as to recover the DC voltage and maintain stability. Therefore, PI proportional-integral control is introduced, and the constant DC voltage control structure is designed as shown in Figure 5 (c).

For long-distance transmission lines of power system, the line reactance X is much greater than the resistance R, so the resistance R is ignored, and according to the method for calculating power flow lines, the voltage drop on the transmission line can be obtained as:

$$\Delta U = \frac{QX}{U} \tag{13}$$

It can be seen from equation (13) that under the condition of a certain line, the voltage drop is mainly related to the reactive power transmitted by the transmission line; therefore, by controlling the reactive power component, the AC voltage can be adjusted. PI proportional integral control is introduced and the design of the constant AC voltage control structure is as depicted in Figure 5 (d).

3. Control strategy of flexible DC transmission system

3.1 Analysis of Conventional Voltage Droop Control Strategy

The core of conventional DC voltage droop control is to keep MTDC voltage constant by using P-V (or I-V) slope relationship of each converter station. It can be regarded as the combination of constant DC voltage control and constant active power control, and its essence is to participate in active power regulation at the cost of DC voltage static difference, so as to achieve the goal of active power balance without relying on high-speed communication [19]. The principle of this control strategy is to compensate the product of DC voltage deviation and droop coefficient on the basis of DC power reference value [20]. The controller structure is shown in Figure 6.

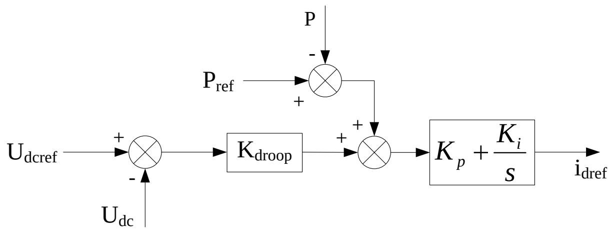


Figure 6. Conventional voltage droop controller structure

In Figure 6, K_{droop} is DC voltage droop coefficient, P_{ref} and P correspond to the reference and measured values of the active power of the converter station, U_{dcref} and U_{dc} are reference and measured values of converter station DC voltage respectively. As follows, the converter station's DC voltage and power relationship during steady-state operation of the system:

$$U_{dc} - U_{dcref} = -\frac{1}{K_{droop}} (P - P_{ref}) \tag{14}$$

From equation (14), the P-V characteristic curve for conventional voltage droop control can be observed in Figure 7.

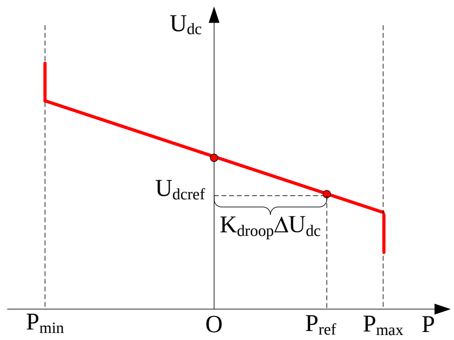


Figure 7. P-V Characteristic Curve of Voltage Droop Control

The droop coefficient K_{droop} is a parameter that determines the performance of the system, and its value is determined by this linear relationship of the P-V characteristic curve. If K_{droop} is large, the droop curve is slow, and the MTDC system's voltage quality is high, but the power distribution characteristic is poor, and the active power transmitted by MMC may exceed the limiting value. If K_{droop} is small, the droop curve is steep, the power distribution characteristic of MTDC system is good, but the voltage quality is poor, and the DC voltage of MMC may exceed the insulation margin.

Therefore, droop coefficient K_{droop} must be selected reasonably, and power distribution characteristics and DC voltage quality must be considered to ensure the normal and stable operation of MMC-MTDC system [21].

3.2 Improved strategy for controlling DC voltage droop

In the conventional voltage droop control strategy, the selection of droop coefficient is very important. If droop coefficient is not selected reasonably, the operation of converter station under complex conditions will be greatly challenged.

In order to avoid the above situation, this paper proposes an improved strategy to controlling DC voltage droops in MTDC systems. Assuming that the real time active power of the ith converter station in the system is P_i, P_{iM} is the maximum power value and P_{im} is the minimum power value, and then P_{iM}-P_{im} represents the power margin of the converter station. Firstly, the active power margin factor H_P is introduced, and its expression is:

$$H_P = \frac{P_i - P_{im}}{P_{iM} - P_{im}} \tag{15}$$

Equation (15) indicates that the active power margin factor H_P is inversely proportional to the power margin under the current operation state of the converter station. When the power margin factor H_P <0.5, the actual active power of the converter station deviates far from the rated value, and its power margin is large. When H_P> 0.5, the converter station real-time active power is close to the rated value, and its power margin is small; if the converter station continues to bear unbalanced power at this time, it will switch to constant power control. Therefore, the power margin factor H_P is introduced into the droop factor, forming a new droop factor K'_{droop} as:

$$K'_{droop} = \frac{\beta K_{droop}}{H_P} \tag{16}$$

Where, β is a constant to prevent large sag coefficient deviations from affecting unbalanced power.

The stability and safety of the VSC-MTDC system can be evaluated through the use of DC voltage deviation as a significant index. When the active power of the system is greatly disturbed, the converter station will lose its power distribution ability and produce large DC voltage deviation, thus affecting the safe and stable operation of the system. To avoid the above problems, DC voltage deviation can be used to change the droop coefficient operating point, and DC voltage can be maintained in a reasonable range by selecting a reasonable reference value [22]. The expression for the DC voltage reference value U'_{dcref} is:

$$\begin{cases} U'_{dcref} = \alpha U_{dcref} - U_{dcref} \\ \alpha = 2 - \dfrac{\mu}{\varphi - \Delta U_{dc}} \end{cases} \tag{17}$$

Where, α is the voltage reference coefficient, μ is the constant controlling the DC voltage influence weight, φ is the DC voltage margin coefficient, and ΔU_{dc} is the DC voltage deviation.

Substituting equations (16) and (17) into equation (14), the relationship between DC voltage and power of converter station under improved DC voltage droop control strategy is:

$$U_{dc} - \alpha U_{dcref} + U_{dcref} = -\frac{H_P}{\beta K_{droop}}(P - P_{ref}) \tag{18}$$

It can be obtained from Equation (18) that the structure of the improved DC voltage droop controller is shown in Figure 8.

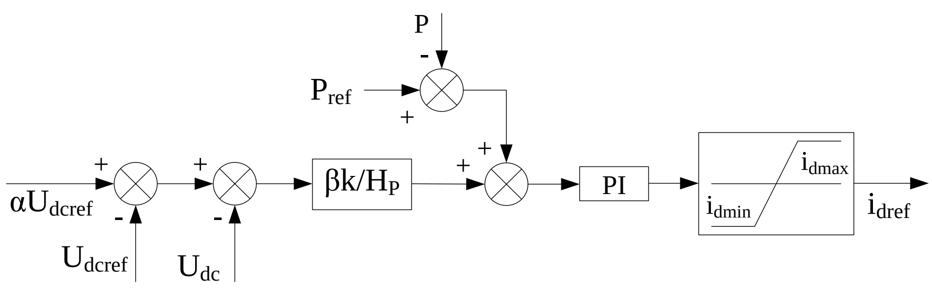


Figure 8. Improved DC voltage droop controller structure

4. Simulation Test Analysis of Wind Power Via Flexible DC Transmission System

In order to verify that the proposed DC voltage droop control strategy can maintain DC voltage constant and its feasibility in the application of wind power grid-connected flexible DC transmission system, a three-terminal VSC-MTDC system model including wind farms is constructed by Matlab/Simulink. According to different conditions of power fluctuation caused by wind power output variation, simulation and analysis of VSC active power and DC voltage variation are carried out. The simulation structure is shown in Figure 9.

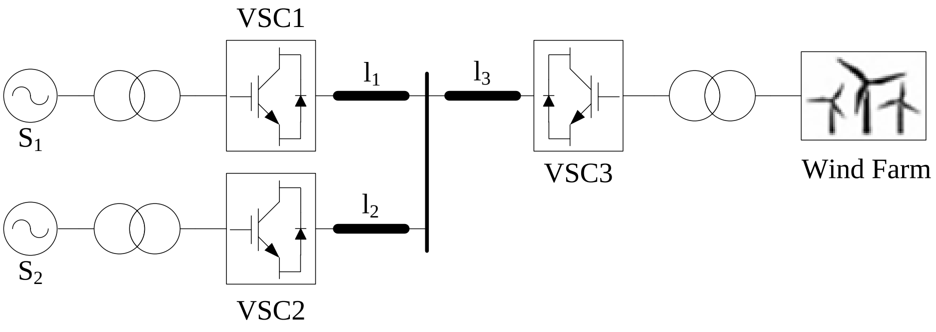


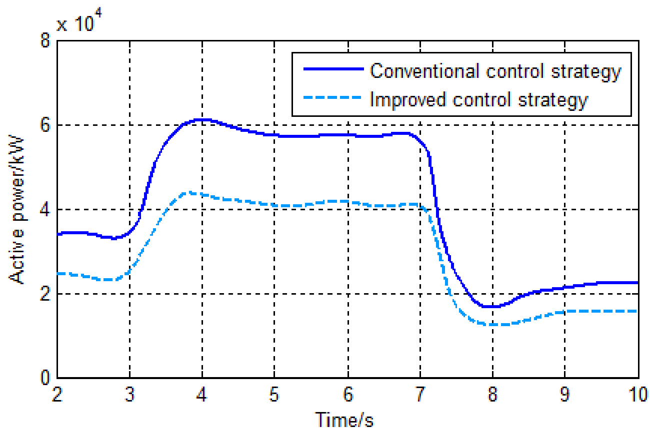
Figure 9. Simulation structure diagram

The system simulation process's main parameters are depicted in Table 1[3].

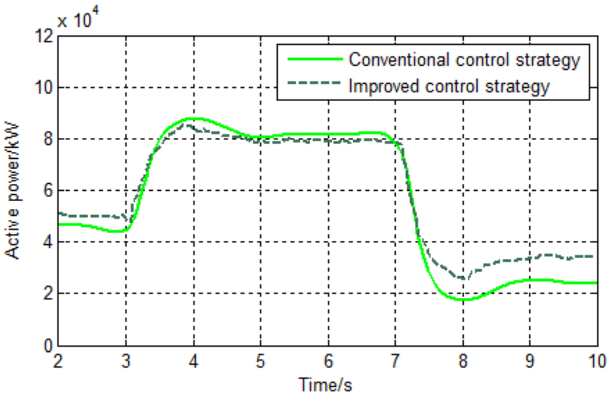
Table 1. System simulation parameters

parameter	numerical value	parameter	numerical value
VSC1 Rated Capacity/MW	100	DC voltage rating/kV	100
VSC2 Rated Capacity/MW	200	VSC1 Initial droop factor	1e-6
VSC3 Rated Capacity/MW	200	VSC2 Initial droop factor	0.5e-6
Line l_1 Length/km	40	Line resistance R/(Ω/km)	1.39e-2
Line l_2 Length/km	60	Line inductance L/(H/km)	1.59e-4
Line l_3 Length/km	40	Line Capacitance C/(F/km)	2.31e-7

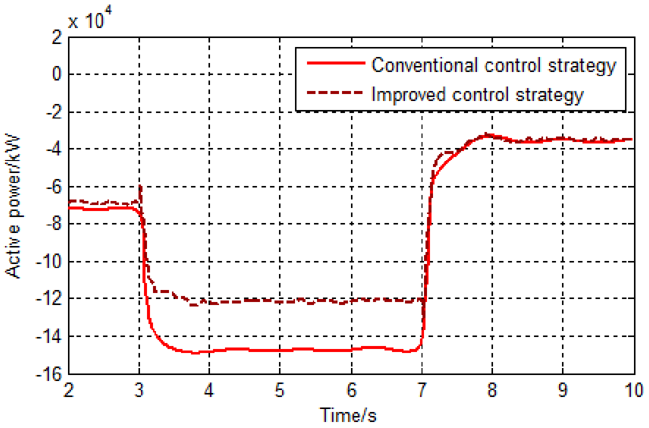
Set the initial value of wind speed as 8m/s, the wind speed suddenly increases to 12m/s at 3s, and the wind speed suddenly decreases to 6m/s at 7s. VSC1 and VSC2 utilize the voltage droop control method, while VSC3 adopts for a constant AC voltage control mode. The VSC-MTDC system is simulated by using the conventional DC voltage droop control strategy and the improved strategy for controlling DC voltage droop respectively. Assuming that the power flows from the DC side to the AC side of the VSC in the positive direction, the comparison of the active power changes of each VCS under the two control strategies is shown in Figure 10.



(a)Comparison of VSC1 active power variation



(b)Comparison of VSC2 active power variation

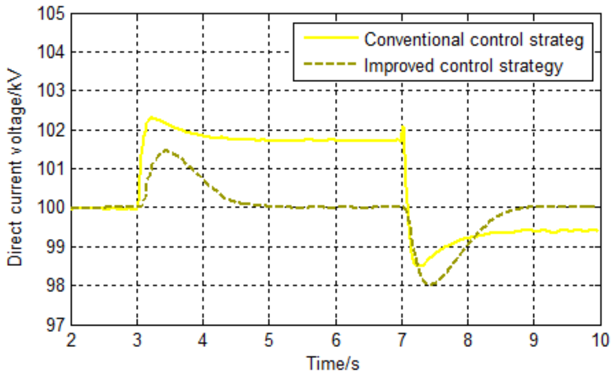


(c)Comparison of VSC3 active power variation

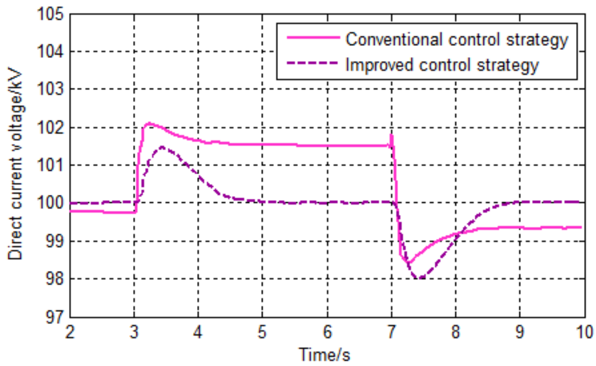
Figure 10. Comparison of Active Power Variation of VCS under Two Control Strategies

Figure 10 indicates that when the wind speed abruptly increases from 8m/s to 12m/s, under the conventional DC voltage droop control strategy, the maximum power increase of VSC1 is 2.8 kW, and the maximum power increase of VSC2 is 4.4 kW; under the improved strategy for controlling DC voltage droop, the maximum power increase of VSC1 is 2 kW, and the maximum power increase of VSC2 is 3.8 kW. When the wind speed drops abruptly from 12m/s to 6m/s, the maximum power reduction of VSC1 and VSC2 is 4.5 kW and 7kW respectively under the conventional DC voltage droop control strategy; and the maximum power reduction of VSC1 and VSC2 is 3.2 kW and 6kW respectively under the improved strategy for controlling DC voltage droop. With the change of wind farm output, VSC1 and VSC2 can change active power along their droop curves under two control strategies. However, under the conventional DC voltage droop control strategy, the received power of each converter station is distributed according to a fixed proportion, the power variation amplitude is larger, and the power variation is higher. However, under the improved strategy for controlling DC voltage droop, the amplitude of power variation is relatively small, and the power variation is lower. Therefore, the improved strategy for controlling DC voltage droop proposed in this paper makes the converter station retain more power regulation margin when the converter station absorbs more active power, and can prevent the converter station from losing its power regulation ability when the power reaches the upper limit.

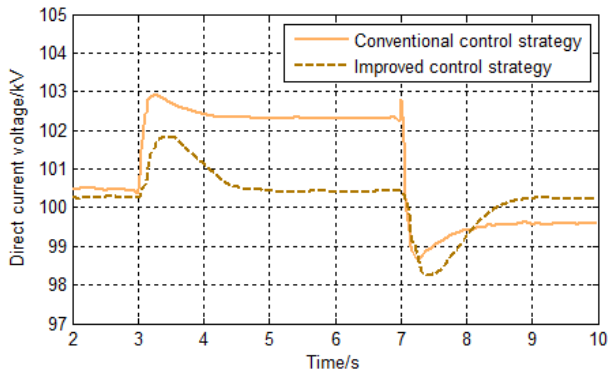
Based on the same simulation parameter settings as above, The VSC-MTDC system's simulation is done by utilizing the conventional DC voltage droop control strategy and the improved strategy for controlling DC voltage droop respectively, and the DC voltage variation of each VCS under the two control strategies is analyzed. Figure 11 displays the comparison of simulation results.



(a)VSC1 DC voltage variation comparison



(b)VSC2 DC voltage variation comparison



(c)VSC3 DC voltage variation comparison

Figure 11. Comparison of DC voltage variation of VCS under two control strategies

Figure 11 indicates that the sudden increase of wind speed at 3s leads to the increase of wind power and DC voltage. Under the conventional DC voltage droop control strategy, the DC voltage of VSC1 tends to be stable at 4.1s with a voltage deviation of 1.7kV, and the DC voltage of VSC2 tends to be stable at 4.6s with a voltage deviation of 1.5kV. Under the improved strategy for controlling DC voltage droop, both VSC1 and VSC2 tend to be stable at DC voltage 4.8s, and the voltage deviation is 0kV. At 7s, the wind speed suddenly decreases, the wind power decreases, and the DC voltage decreases. Under the conventional DC voltage droop control strategy, the DC voltage of VSC1 tends to be stable at 8.2s, and the voltage deviation is 0.7kV; the DC voltage of VSC1 tends to be stable at 8.4s, and the voltage deviation is 0.7kV. Under the improved strategy for controlling DC voltage droop, the DC voltages of VSC1 and VSC2 tend to stabilize at 8.8 s, and the voltage deviation is 0kV. Compared with the conventional DC voltage droop control strategy, the larger the wind speed changes, the larger the wind power changes, the more obvious the DC voltage changes, and there is obvious voltage deviation phenomenon. Under the improved strategy for controlling DC voltage droop, the voltage deviation is zero, the fluctuation of DC voltage is small, and it can be basically maintained constant.

5. Conclusions

The VSC-MTDC system is characterized by low transmission costs, high energy efficiency, and high operational reliability. But its control strategy is complex, and the fluctuation of DC voltage directly affects the stable operation of the system. In view of the conventional DC voltage droop control strategy, the received power of each converter station is distributed according to a fixed proportion, the power variation amplitude is larger, the power variation is higher, and the power reaches the upper limit, and the power regulation ability is easily lost; and the greater the power variation, the more obvious the DC voltage variation, and the obvious voltage deviation phenomenon exists. An improved strategy for controlling DC voltage droop was proposed in this paper. A three-terminal VSC-MTDC system model including wind farm was established by Matlab/Simulink. According to different conditions of power fluctuation caused by wind power output variation, simulation and analysis of VSC active power and DC voltage variation were carried out. Simulation results showed that the improved strategy for controlling DC voltage droop proposed in this paper made the converter station retain more power regulation margin when the converter station absorbed more active power, and could prevent the converter station from losing its power regulation ability when the power reached the upper limit, and realized reasonable power distribution among converter stations. Meanwhile, the proposed control strategy could maintain DC voltage constant, which verified the feasibility of its application in wind power grid-connected flexible DC transmission system.

However, this study has several limitations. Firstly, due to the relatively small sample size of line length and wind speed variation, the results may have some bias, which limits its wide applicability. Secondly, this study is mainly aimed at wind power grid-connected flexible DC transmission system; in other types of power systems may show different working mechanisms. In addition, considering the limitation of Matlab/Simulink simulation conditions, the results of this study need to be verified in different actual wind power systems. Therefore, future research should adopt a wider range of experimental samples and more diverse power system background conditions to further verify and expand the conclusions of this study.

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