Active power translation droop control method for converter station of MTDC system

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Abstract. The DC transmission system with wind farm has the characteristics of power and frequency follow-up, it is difficult to realize the stable control of power and voltage in the common control mode of converter station. In order to improve the steady-state characteristics of the active power control of the multi-terminal HVDC (MTDC) power system with wind farms, to eliminate the static deviation existing in the system and avoid the system overvoltage during the operation, the model for MTDC system with wind farms was established and analysed. And a control strategy for p-u sagging curve translation through power measurement is proposed in this paper. A four-terminal VSC-MTDC simulation model in the Matlab/Simulink platform is built. And the proposed MTDC system control strategy is verified under the different simulation conditions. It can ensure that the system transmits active power within the rated capacity range and the DC voltage of the converter stations is stable and accurate.

1. Introduction
The depletion of fossil energy urgently requires the strategic adjustment of the energy structure in all countries of the world. Using large-scale new energy to generate electricity is an alternative to fossil energy, which is the fundamental way to transform energy. It is also an important feature of the new generation of power systems. In the special occasion where wind power is connected to the grid and to the islands or remote areas where there is no AC voltage support, the multi-terminal HVDC transmission (MTDC) system based on voltage source converter station has become a new direction of power transmission. It has also become a useful supplement to the power grid and an important component of the power grid [1]. The rapid development and application of fully-controlled devices make the MTDC technology based on voltage source converters more prominent than traditional HVDC transmission technology [2]. The technology can instantaneously realize independent decoupling control of active and reactive power, can supply power to passive networks and easily form a multi-terminal DC system, and has advantages in improving system stability and transmission capability.

At present, the DC voltage control strategy of MTDC system has different control strategies and methods such as master-slave control, DC voltage slope control and DC voltage margin control. The DC voltage margin control [3] does not require communication between converter stations. When the operating power of the converter station which is responsible for DC voltage stability control reaches its operating threshold, the other converter stations will detect the deviation of the voltage and switch to
the DC voltage control mode when the deviation threshold is exceeded, thereby the DC voltage stability control of the entire system is realized. The ref. [4] presented a scheme of adjusting the droop coefficients to share the burden according to the available headroom of each converter station in the MTDC system. A coordinated control strategy of VSC-MTDC named master-auxiliary is proposed in ref. [5] by combining the advantages of the voltage margin and voltage droop control. In ref. [6], a robust probabilistic controller tuning method was presented to improve the damping of critical system modes through the modulation of active power injected by a voltage-source converter-based multi-terminal high-voltage direct current (VSC-MTDC) grid. A novel control strategy with distributed slack nodes is proposed in ref. [7] by means of a DC optimal power flow. An analytical expression for estimating the distribution of balancing power which accounts for dc line voltage drops is derived in ref. [8]. In order to ensure the maximum power output of the wind farm, while maintaining the stability of the DC side voltage of the converter station, an active power margin to achieve DC voltage stability control strategy based on the coupling relationship between the transmission power of the converter station and the DC voltage is proposed in this paper. It ensures the stable control of DC voltage and the dynamic and effective follow-up of transmission power under the condition that the transmission power of the system does not exceed the rated capacity.

2. Establishment and Analysis of Model for MTDC System with Wind Farm

The typical MTDC system topology connected wind farm is shown in Fig. 1. The system includes n wind farm converter stations and m AC network side converter stations, and together with the DC network to form the system.

![Figure 1. Topological structure of MTDC system with wind farm.](image)

2.1. Wind farm equivalent model establishment

Because the traditional modeling methods are difficult to reflect the internal characteristics of the wind farm's MTDC system, it is necessary to establish an integrated transient simulation model based on the dynamic characteristics of the DC network and the connected AC system and the wind farm power characteristics.

2.1.1. Wind speed model. The analysis results show that the wind speed change in this area is similar to the Weibull distribution[9], and its distribution function can be expressed as:

\[ F_w(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{c}\right)^k\right] \]  

(1)

Where: k is the shape factor, the general value range is 1.8-2.3; \(c\) is the scale factor, which reflects the average wind speed in the described area. The k and c can be obtained by the measured wind speed data analysis. The wind speed samples of a certain area can be generated by Weibull distribution random number \(v_i = c \cdot \left[-\ln(x_i)\right]^{1/k}\). The \(x_i\) is a random number uniformly distributed in the interval [0, 1].
2.1.2. Wind turbine model. Wind turbine wind energy capture is achieved by wind turbine blades. Therefore, the mechanical torque acting on the hub can be used to convert wind energy [10]. According to the power characteristic expression equation of the wind turbine, the mechanical power expression of the wind turbine in the wind farm is obtained:

\[ P_m = \frac{1}{2} \rho \pi R^3 v^3 C_p \]  

(2)

Where: \( P_m \) represents the mechanical power of the wind turbine, \( C_p \) represents the conversion efficiency coefficient of wind energy, \( R \) represents the blade radius of the wind turbine, \( \rho \) is the air density, and \( v \) is the wind speed. In the wind farm, the doubly-fed wind power generator is mainly used, and the electromagnetic power \( P_e \) of the asynchronous generator is:

\[ P_e = \frac{m_i p U_N^2 R'_2 / s}{2 \pi f_1} \frac{2 \pi f_1}{p} \]

(3)

Where: \( m_i \) represents the number of phases of the voltage, \( s \) represents the slip of the asynchronous generator, \( f_1 \) is the frequency; \( \rho \) is the logarithm of the magnetic pole, \( U_N \) is the terminal voltage of the generator. \( R_1, R'_2 \) and \( X_{1o}, X'_{2o} \) respectively represent the equivalent resistance and equivalent reactance of the stator and rotor of an asynchronous generator. Since \( s \) is small in the steady-state operating state, and \( R'_2/s \) is much larger than \( R_1, (X_{1o}+X'_{2o}) \), so \( R_1, (X_{1o}+X'_{2o}) \) can be ignored, thereby obtaining:

\[ P_e \approx \frac{m_i p U_N^2}{2 \pi f_1 R'_2 / s} \frac{2 \pi f_1}{p} = \frac{m_i s U_N^2}{R'_2} \]

(4)

In practice, the functional relationship between the active power \( P_W \) of the fan output and the wind speed \( v \) can be approximated as:

\[ P_W = \begin{cases} 
0, & v \leq v_{ci} \\
k_1 v + k_2, & v_{ci} < v < v_{ri} \\
0, & v \geq v_{co} \\
 Pe, & v_{ri} < v < v_{co} 
\end{cases} \]

(5)

Where: \( k_1 = \frac{P_e}{(v_r - v_{ci})} \), \( k_2 = -k_1 \cdot v_{ci} \), \( P_e \) is the rated power of the wind turbine, and \( v_{ci}, v_{ri}, v_{co} \) are the cut-in wind speed, the rated wind speed, and the cut-out wind speed. According to the wind speed random probability model and the wind turbine output power model expression, the expression of the output power probability density of the wind turbine can be derived as follows:

\[ f(P_W) = \begin{cases} 
\int_0^{v_{ci}} F_w(v) dv + \int_{v_{ci}}^{v_{ri}} F_w(v) dv & P_W = 0 \\
\frac{k_1 c}{k_2 c} \cdot \exp\left(\frac{P_w - k_2}{k_1 c}\right) & 0 < P_W < P_e \\
\int_{v_{ri}}^{v_{co}} F_w(v) dv & P_W = P_e 
\end{cases} \]

(6)

Through the basic principle of generator operation, the relationship between the reactive power \( Q \) absorbed by the asynchronous fan and the active power of the output and the terminal voltage \( U \) is derived:

\[ Q = -\frac{U^2}{x_m} + \frac{-U^2 + \sqrt{U^4 - 4P^2x_k^2}}{2x_k} \]

(7)

Where: \( x_m \) represents the excitation reactance, \( x_1 \) represents the leakage reactance of the stator, \( x_2 \) represents the leakage reactance of the rotor, \( x_k = x_1 + x_2 \), the stator resistance is neglected, and \( P \) is the active power of the motor output.
2.1.3. Wind farm capacity weighted single machine equivalent model. In the same wind farm, all wind turbines are connected to the same bus through the outlet transformer, while ignoring the influence of impedance on the cable lines connecting adjacent wind turbines. Assuming that the wind farm is composed of N typhoon generators, the wind farm is equivalent to a generator set, retaining the fan and wind speed model and superimposing the mechanical torque of the fan, and taking it as the input of the equivalent generator. The equivalent parameters can be obtained as follows:

\[
\begin{align*}
S_{eq} &= \sum_{i=1}^{N} S_i \\
N_{eq} &= \sum_{i=1}^{N} P_i \\
C_{eq} &= \sum_{i=1}^{N} C_i \\
Z_{Geq} &= \frac{Z_G}{N} \\
Z_{Teq} &= \frac{Z_T}{N} \\
T_{sum} &= \sum_{i=1}^{N} T_i
\end{align*}
\] 

(8)

2.2. DC Power Network Model Connected by AC/DC

![Diagram of N-terminal MTDC transmission network](image)

**Figure 2.** Schematic diagram of N-terminal MTDC transmission network

The transmission network of an MTDC system with an n-terminal DC line is shown in Fig.2. In the AC/DC model, the three-phase AC network configuration model is shown in Fig.3. In order to control the active power and reactive power of the converter, the \(dq\) transform can control the active power and reactive power instantaneously, and control them in a decoupled way. The control variables will be the direct flow in a stable state. Therefore, the converter can be controlled by using \(dq\) transform in this model. The relationship between AC voltage source on AC side and AC voltage on converter side can be expressed as follows:

\[
U_{a,i} - V_{a,i} = L_i \frac{di_{a,i}}{dt} + R_i i_{a,i}
\]

(9)
Convert the equation to the $dq$ reference coordinate system, the following relational expression can be get:

\[
\begin{bmatrix}
    U_{d,i} \\
    U_{q,i}
\end{bmatrix} =
\begin{bmatrix}
    R_i & -\omega L_i \\
    \omega L_i & R_i
\end{bmatrix}
\begin{bmatrix}
    I_{d,i} \\
    I_{q,i}
\end{bmatrix} +
\begin{bmatrix}
    L_i & 0 \\
    0 & L_i
\end{bmatrix}
\begin{bmatrix}
    d I_{d,i} \\
    d I_{q,i}
\end{bmatrix}
\]

(10)

Where: $I_{d,i}$ and $I_{q,i}$ are the d-axis and q-axis components of the current flowing from the AC grid to the converter station converter, $U_{d,i}$ and $U_{q,i}$ are the d-axis and q-axis components of the AC voltage source, assuming $i$ is the constant, finally $V_{d,i}$ and $V_{q,i}$ are the d-axis and q-axis components of the AC side voltage of the $i$-th converter station.

Therefore, the dynamic model of terminal $i$ can be described by a set of differential equations (for $i = 1, 2, 3, ..., n$), and the general form of the dynamic model equation for terminal $i$ is expressed as:

\[
\begin{aligned}
    \dot{I}_{d,i} &= \frac{-R_i I_{d,i} + \omega L_i I_{q,i}}{L_i} + \frac{U_{d,i}}{L_i} - \frac{V_{d,i}}{L_i} \\
    \dot{I}_{q,i} &= \frac{-R_i I_{q,i} + \omega L_i I_{d,i}}{L_i} + \frac{U_{q,i}}{L_i} - \frac{V_{q,i}}{L_i}
\end{aligned}
\]

(11)

(12)

From Fig.2., the relationship between the alternating part and the direct current part of the i-th converter station can be expressed as:

\[
\dot{V}_{dc,i} = \frac{P_{inj,i}}{V_{dc,i} C_i} - \frac{I_{dc,i}}{C_i}
\]

(13)

The active power exchange with the i-th AC grid is expressed as:

\[
P_{s,i} = U_{d,i} I_{d,i} + U_{q,i} I_{q,i}
\]

(14)

And the active power received by i-th converter is:

\[
P_{conv,i} = U_{d,i} I_{d,i} + U_{q,i} I_{q,i} - R_i (I_{d,i}^2 + I_{q,i}^2)
\]

(15)

Assuming that the converter is ideally lossless, there are:

\[
P_{inj,i} = P_{conv,i}
\]

(16)

The reactive power exchanged with the AC grid $i$ can be expressed as:

\[
Q_{s,i} = U_{q,i} I_{d,i} - U_{d,i} I_{q,i}
\]

(17)

When using a phase-locked loop, the d-axis component of the $dq$ reference coordinate system will be aligned with $a$ of the $abc$ reference coordinate system. Assuming PLL tracking is ideal, with $U_{q,i} = 0$, then equations (14) and (17) can be expressed as [98]:

\[
P_{s,i} = U_{d,i} I_{d,i}
\]

(18)
\[ Q_{s,i} = -U_{d,i} I_{q,i} \]

Therefore, \( P_{s,i} \) is controlled by \( I_{d,i} \), and \( Q_{s,i} \) is controlled by \( I_{q,i} \).

3. Converter Station Control Strategy Design

![Figure 4. Diagram of P and DC voltage slope control characteristic](image)

In order to improve the steady-state characteristics of the active power control of the MTDC system with wind farms, to eliminate the static deviation existing in the system and avoid the system overvoltage during the operation, a control strategy for p-u sagging curve translation through power measurement is proposed in this paper. The droop curve characteristics are shown in Fig.4. Where: \( U_{H} \), \( U_{L} \) respectively represent the rising threshold and falling threshold of the output DC voltage of the converter station; \( U^*_{dc} \) represents the given DC voltage value. When the DC voltage and the active power are within the normal threshold range, the converter station operates on the solid curve of the U-P characteristic. When the measured value of the active power is a given value, the voltage reference value remains constant. When the measured value of the active power is inconsistent with the set value, the difference between the active set-point and the actual measured value becomes the additional value of the voltage set-point after the integral controller, and the drooping curve is realized by changing the DC voltage set-point indirectly. The translation control of the droop curve can be continuously adjusted in real time, which is convenient for eliminating the DC voltage and the static error of the active power. The translation control of the droop curve can be continuously adjusted in real time, which is convenient for eliminating the DC voltage and the static error of the active power.

The structure of the controller is shown in Fig.5. The schematic diagram of the direct control principle of the converter station is shown in Fig.6. In the outer loop control, according to the reference value given by the system, the difference between the actual measured value and the reference value is outputted by the PI controller to the given current command of the inner loop, thereby realizing the stable control of DC voltage, the active power, the reactive power, and the frequency. The current inner loop is controlled according to the current command given by the outer loop. The difference between the given current value and the actual measured current value is also obtained by the PI controller, and finally the modulation trigger pulse signal is obtained. Fig.4 is a schematic diagram showing the structure of the direct control principle of the converter station. Where \( A_{ref} \) is the active variable related control variable and \( B_{ref} \) is the reactive power related control variable.
4. Simulation Research
In order to verify the dynamic performance and correctness of the control strategy, the 4-terminal MTDC system simulation model as shown in the fig.1 is built by Matlab/Simulink simulation software. The converter stations 1 and 2 were connected respectively to the sending end wind farms 1 and 2. The converter stations 3 and 4 were connected respectively to the receiver AC systems 1 and 2. System parameters settings are shown in Table 1. The specific simulation conditions are set as shown in Table 2.

| Parameters                                                                 | Values                        |
|----------------------------------------------------------------------------|-------------------------------|
| MTDC system rated capacity/MVA                                             | 2000                          |
| Converter station rated capacity /MVA                                      | 200                           |
| Grid line voltage /kV                                                      | 230                           |
| DC bus voltage /kV                                                         | ±100                          |
| Sampling frequency /kHz                                                    | 10                            |
| AC filter capacitor /M var                                                 | 40                            |
| DC side flat wave capacitor /F                                              | 1.4×10^{-4}                   |
| DC side filter capacitor /F                                                | 2.4×10^{-5}                   |
| DC side flat wave electrical impedance transmission line length /km        | 0.0251Ω+8×10^{-3}H            |

Figure 5. Structural diagram of translational drop curve control characteristic

Figure 6. Schematic diagram of direct control for converter station
Table 2. Simulation conditions setting

| Simulation conditions | Default setting | Final setting | Changing setting |
|-----------------------|----------------|--------------|-----------------|
| P=0.0 p.u. > 0.5 p.u. | Q=0.0 p.u.   | P=0.5 p.u.   | Steady state operation |
| U_{dc}=1.0 p.u.      |               | U_{dc}=1.0 p.u. |                |
| 1                     |                |              |                 |
| P=0.0 p.u. > 0.5 p.u. | Q=0.0 p.u.   | P=0.5 p.u.   | Wind farm disturbance |
| U_{dc}=1.0 p.u.      |               | U_{dc}=1.0 p.u. |                |
| 2                     |                |              |                 |
| P=0.0 p.u. > 0.5 p.u. | Q=0.0 p.u.   | P=0 p.u.     | Active power inversion |
| U_{dc}=1.0 p.u.      |               | U_{dc}=1.0 p.u. |                |
| 3                     |                |              |                 |

4.1. Four-terminal steady-state operation test

Set the system according to simulation condition 1 in Table 1. The simulation results of steady-state operation under the active power translation droop control strategy are shown in Fig.7 to Fig.9.

It can be seen from Fig.7 that the active power of the converter station gradually increases from 0.0 p.u. according to the power slope to 0.5 p.u., and the active power of the converter station only fluctuates in a short period of time within 0.15 s of the system startup, and the two-feed end converters after 0.15 s. The active power of the station can accurately track the reference value of the active power to the steady-state operating value of 0.5 p.u., which ensures the stable transmission of the active power of the converter station at the sending end. It can be seen from Fig.8 that the reactive power of the four converter stations fluctuates in a short period of time within 0.15 s of the system startup, and the reactive power of the four converter stations can accurately track the reference value of the reactive power after 0.15 s. It can be seen from Fig.9 that the DC voltage of the converter stations, which are connected to the AC system. There is a short-term fluctuation in the starting time of 0.1 s. After 0.1 s, the DC voltage of each converter station can accurately track the reference value of the DC voltage to a steady-state operating value of 1.0 p.u. The two-feed converter station has a negligible small fluctuation in the process of the active power rising to the steady-state value according to the given slope. The DC voltage is fast and stable after the active power is stabilized, which ensures the stable transmission of the active power of the converter station at the feed end. The DC voltage of the receiving converter station is stable, and the DC voltage control performance of the receiving converter station is superior, and the dynamic response characteristics are good.

**Figure 7.** Active power dynamic curves of sending and receiving converter station
4.2. Small disturbances test of wind farm

In the actual operation process, the wind farm will be affected by various factors such as weather and wind speed changes. Therefore, the uncertain disturbance caused by the wind farm AC system is a common phenomenon in the actual system. Therefore, it is necessary to verify the control performance of the system in the case of disturbance caused by the wind field AC measurement system. An AC system disturbance with the duration of 0.05s which is set at 1.5s on the AC side of the sending end wind farm 1 and an AC system disturbance of 0.05s duration is set at 2.0s of the sending end wind farm 2. Other parameters were set according to simulation condition 2 in Table 1. The simulation results are shown in Fig.10 to Fig.11.

Figure 8. Reactive power dynamic curves of sending and receiving converter station

Figure 9. Dynamic DC voltage curves of sending and receiving converter station
Figure 10. Active power dynamic curves of sending and receiving converter stations under wind farm disturbances

Fig. 10 (a) shows the dynamic overall dynamic running curve of the active power at the sending end and the receiving end converter station under the disturbance of the sending end wind farm. Fig. 10 (b) shows the partial amplification curve before and after 1.5s to 2.0s. It can be seen from the figure that when the wind-exchange station 1 has AC disturbance in the wind farm at 1.5s, its active power fluctuates slightly, reaching a maximum of 0.6 p.u., deviating from the given value by 0.1 p.u.. And the fluctuation duration is about 0.15s. At this time, the fluctuation of the active power of the converter station 2 is much smaller, the maximum value is 0.52 p.u., and the deviation is 0.02 p.u., and the AC disturbance on the wind side has less influence on the active power of the other converter station. The converter station 2 is similarly affected by wind farm disturbances at 2s.

Figure 11. Reactive power dynamic curves of sending and receiving converter stations under wind farm disturbances

Fig.11 (a) shows the reactive power dynamic curves of the converter station 1 and 2 under the disturbance of the sending end wind farm. The reactive power of the converter station 1 maintains a stable value of about -0.8 p.u. The reactive power of the converter station 2 shows a small fluctuation, with a maximum value of -0.4 p.u. and a deviation of 0.02 p.u. The AC disturbance on the wind side has less influence on the reactive power of the other converter station. The converter station 2 is similarly affected by wind farm disturbances at 2s.
The active power of the two receiving converter stations 3 and the converter station 4 has small active power fluctuations at 1.5s and 2.0s, and the maximum deviation of the fluctuation amplitude is 0.025p.u.. The active power of the converter station at the sending end has a certain influence, and other converter stations are much less affected by it. The active power of the four converter stations can always follow the given value change, and the fluctuation of the AC system of the receiving end is less affected. After the disturbance disappears, it can quickly follow the given value of the active power, and the dynamic performance is superior and robust.

Fig.11 (a) is the dynamic overall dynamic curve of reactive power of the sending end and the receiving end converter stations under the disturbance of the sending end wind farm. Fig.11 (b) shows the partial amplification curve before and after 1.5s to 2.0s. It can be seen from the figure that the AC disturbance of the wind farm has a great influence on the reactive power output from the converter stations at the sending end, and the maximum fluctuation of the reactive power of the corresponding converter station is -0.1p.u., and the maximum deviation value reaches 0.1p.u.. It has little effect on the reactive power output of other converter stations. The reactive power of the two receiving end converters will be affected by the AC disturbance of the two sending ends, but the impact is relatively small. The maximum deviation is 0.01p.u.. Therefore, the disturbance of the AC system of the wind farm only has a certain influence on the reactive power of the converter station at the end, and the other converter stations are less affected by it, and the receiving converter station is almost unaffected by it. The reactive power of the four converter stations can follow the given value, and the fluctuation of the AC system of the sending end is less affected.

4.3. Control Performance Test of Converter Station under Active Power Inversion

The wind farm generally transmits power to the outside under the condition of sufficient wind energy, and absorbs power from the external network in the case of insufficient wind energy. Therefore, it is necessary to have a power reverse transmission function for the soft straight system. When power reversal is required, the active controller needs to give a negative power to set the target value. The active power of the converter stations 1 and 2 at the sending end changes from 0.5p.u. to -0.5p.u. in accordance with the set change slope at 1.5s. Other parameters were set according to simulation condition 3 in Table1. The simulation results are shown in Fig.12 to Fig.13.

Fig.12 (a) (b) corresponds to the active power dynamic running curve and the partial amplification curve of the sending and the receiving end of converter stations under active power inversion of sending converter stations. It can be seen from the figure that the active power of the converter stations quickly
follows the given value from 0.5pu to -0.5pu in accordance with a given slope at 1.5s. The fast tracking performance is superior, and there is almost no fluctuation of active power in the whole process. The active power of the two receiving converter stations can also follow the change of the active power of the sending end synchronously, and the output power state is stable from the absorbed power state, and the whole process has almost no fluctuation. The active power of the four converter stations can always follow the given effective reversal of the active power, the system fluctuation is small, and the dynamic performance is superior.

![Figure13. DC voltage dynamic curves of sending and receiving converter stations under active power inversion of sending converter stations](image)

Fig. 13 (a) (b) shows the overall curve and partial amplification curve of DC voltage dynamic curves of sending and receiving converter stations under active power inversion of sending converter stations. From the partial amplification curve, it can be obtained that the DC voltage of the four converter stations has a DC voltage drop of 0.9s during the active power reversal of the converter stations at the sending end, and the maximum deviation is 0.04pu.. In other stages, the DC voltage of the stations always maintains the set value of the controller, and the DC voltage of the converter stations at the sending end also maintains the set value of the system. The anti-interference performance is superior.

5. Conclusion
In order to improve the steady-state characteristics of the active power control of the MTDC system with a wind farm, eliminate the static deviation of the system and avoid overvoltage in the system during operation, a control strategy for p-u sagging curve translation by indirect measurement of active power is proposed. Under the different simulation conditions, the proposed MTDC system control strategy is verified. The method can ensure that the system transmits active power within the rated capacity range. Under the control strategy, the DC voltage of the converter stations is stable and accurate. The deviation is small, the dynamic response is fast, and the robustness is good.
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