Optimal Power distribution method for wind farms to enhance the FRT capability of the LCC-HVDC system under commutation failure

Xiao. Jin¹, Heng. Nian¹, Senior Member, IEEE, Bo. Pang²

¹College of Electrical Engineering, Zhejiang University, Hangzhou, China
²State Grid Sichuan Economic Research Institute, Chengdu, China

Corresponding author: Heng. Nian (e-mail: nianheng@zju.edu.cn).

ABSTRACT Line-commutated converter (LCC) based high-voltage direct current (HVDC) technology is a common technology for long-distance transmission of electricity. Commutation failure is a common fault in the LCC-HVDC transmission system, which brings new challenge to the stable operation of wind turbines on the sending AC grid. It is necessary to suppress the overvoltage of the sending AC grid to improve the fault ride-through (FRT) capability of the LCC-HVDC system under commutation failure. The voltage amplitude of the sending AC grid is affected by the power characteristics of the wind farms on the sending AC grid. Based on the analysis of the mathematical relationship between the reactive power of the wind farms and the overvoltage of sending AC grid and the mathematical relationship between the reactive power absorption capacity of the wind farms and the active power of the wind farms, the overvoltage of the sending AC grid can be suppressed by redistributing the power of the wind farms. An optimized power distribution method for wind farms is proposed to suppress the overvoltage of the sending AC grid and improve the FRT capability of the LCC-HVDC system under commutation failure. The effectiveness of the proposed optimal method is verified through two cases by building the simulation model based on Matlab/Simulink.

INDEX TERMS Wind farm, Commutation failure, Fault ride-through (FRT), Line-commutated converter (LCC) based high-voltage direct current (HVDC), Overvoltage suppression.

I. INTRODUCTION

Line-commutated converter (LCC) based high-voltage direct current (HVDC) technology is a commonly used long-distance transmission technology [1]. In recent years, a lot of ±800kV and ±1000kV Ultra HVDC transmission lines based on LCC-HVDC transmission technology have been built in China [2][3].

Commutation failure is a common fault in the LCC-HVDC system, which is caused under weak AC grid and fault conditions [1][4]. It has been pointed out that the sending AC grid in the LCC-HVDC system will produce overvoltage problems under the commutation failure [5][6]. The overvoltage caused by commutation failure will deteriorate the operation of the wind farm on the sending AC grid. According to the technical rule for connecting wind farm to power system, when the grid voltage exceeds 1.3 pu, the wind farm is at risk of being separated from the grid [7]. The fault ride-through (FRT) capability of the LCC-HVDC system under commutation failure is defined as the ability of the equipment on the power grid to not operate offline when a commutation failure occurs. The FRT capability of the LCC-HVDC system under commutation failure is enhanced with the decrease of the peak value of the overvoltage of the sending AC grid. It is necessary to suppress the overvoltage of the sending AC grid under commutation failure to enhance the FRT capability of the LCC-HVDC system [8].

The transient reactive power of the wind farm on the sending AC grid is one of the main factors affecting the overvoltage of the sending AC grid [2][6]. Considering the capacity limitation of wind turbines and converters, the transient reactive power of wind farms is limited by the active power of wind farms [9]. The power distribution method for wind farms is defined as the plan for the active power output of each wind farm in the regional power grid. It can be found that optimizing the power distribution method of the wind farms on the sending AC grid is a
feasible solution to suppress the overvoltage of the grid under commutation failure.

Most of the existing power distribution methods of wind farms are aimed at reducing line losses or improving the economic benefits of wind farms. Keane et al. [10] proposed a reactive power distribution method for wind turbines, which reduces line losses on the basis of ensuring the wind turbines support the voltage at the point of common coupling. Alismail et al. [11] established a distributional robust planning model to determine the optimal allocation of wind farms in a multi-area power system, which minimizes the expected energy not served and improves the economic benefits of the system. Aimed at offshore wind farms connected to the multi-terminal HVDC system, Sun et al. [12] proposed a droop coefficient adjustment method based on analytic hierarchy process to optimize power distribution and maximize the financial benefit to wind producers. Li et al. [13] proposed a power distribution method for wind farms based on energy flow calculation methods, taking the penalty cost of wind curtailment into consideration to maximize the economic value of the power system. According to the proportion of wind turbines and thermal power units, Yang et al. [14] proposed a wind farm power distribution method to improve the primary frequency modulation capability of the wind-thermal power coordination system. The above power distribution methods take line loss and economic benefits as the optimization goals rather than the transient overvoltage under commutation failure, and the wind farms may be disconnected from the grid under the effect of the transient overvoltage under the commutation failure.

The proposed methods to suppress transient overvoltage in the grid connected with large-scale wind farms are mainly divided into two categories: (1) installing reactive power regulation equipment; (2) improving the control strategy. The first category of methods does not require changes to the existing wind farms, which is widely used in engineering applications. Liu et al. [15] proposed that installing static var compensator (SVC) or static compensator (STATCOM) can effectively suppress the transient overvoltage under the commutation failure. Lei et al. [16] proposed that UPFC has the best overvoltage suppression effect compared to SVC and STATCOM. The second category of methods does not require additional hardware equipment, which reduces the cost. Jin et al. [6] proposed a power command delay compensation strategy to speed up the power response speed of wind turbines to suppress the overvoltage of the sending AC grid under commutation failure. Zhou et al. [17] proposed a cooperative power command strategy for wind turbines, which suppresses the active power output under commutation failure so as to increase the reactive power capacity of the wind turbines to suppress transient overvoltage. The existing improved control strategies are mostly aimed at a single wind turbine. The optimal power distribution method proposed in this paper coordinates the control of multiple wind farms in the regional grid to suppress the overvoltage of the sending AC grid.

This paper proposes an optimal distribution method for wind farms to suppress the overvoltage of the sending AC grid under commutation failure. The proposed optimal distribution method maximizes the reactive power absorption capacity of the wind farms by adjusting the active power distribution of the wind farms in the sending AC grid, which improves the FRT capability of the LCC-HVDC system under commutation failure. The main contributions of this paper can be summarized as follows.

1) A mathematical model of multiple wind farms connected to the sending AC grid is established to analyze the impact of increasing the reactive power absorption capacity of the wind farms on the bus voltage of the sending AC grid.

2) The power modulation range of wind farms considering the wind power conditions of the wind farm is calculated to analyze the restriction of generated power to reactive power absorption capacity of the wind farm.

3) An optimal power distribution method of wind farm is proposed to suppress the overvoltage of the sending AC grid and improve the FRT capability of the LCC-HVDC system under commutation failure.

The rest of this paper is organized as follows. Section II analyzes the influence of the reactive power of the wind farms on the bus voltage of sending AC grid and the power modulation range of wind farm. An optimal power distribution method of wind farm is proposed based on the analysis in section II. Section III presents two cases for the proposed optimal power distribution method of wind farms, and a 500kV LCC-HVDC system is built based on Matlab/Simulink for verification. Finally, section IV draws the conclusion.

II. OPTIMAL DISTRIBUTION METHOD OF WIND FARM

A. INFLUENCE OF REACTIVE POWER OF WIND FARMS ON OVERVOLTAGE OF SENDING AC GRID

The influence of the reactive power absorbed by the wind farms on the sending AC grid on the overvoltage of the sending AC grid under commutation failure is quantitatively calculated in part A. [6] established a mathematical model of the voltage fluctuation of the sending AC grid under commutation failure. In the analysis of [6], one wind farm and one thermal power plant are both equivalent as a single voltage source. The mathematical model proposed in this part analyzes the voltage changes of the sending AC grid connected to multiple wind farms.

Fig. 1 shows the topological structure diagram of the LCC-HVDC system. The LCC-HVDC system consists of the sending AC grid, rectifier station, DC transmission line, inverter station, and the receiving AC grid. Several wind farms and a thermal power plant represented by represented by the classic model of a synchronous generator are connected to the sending AC grid [18]. The receiving AC grid is replaced by a simplified voltage source with impedance. Two 12-pulse converter bridges are used in the rectifier station and the inverter station. The AC filter on the sending AC grid and
receiving AC grid can filter the 12th and 24th harmonics currents of the rectifier station and compensate the reactive power of the rectifier station and inverter station. Four smoothing reactors are installed on the DC transmission line to smooth the harmonics of the DC current.

\[
V_{\text{dc}} = r_1 I_{\text{dc}} + X_{\text{dc}} I_{\text{dc}} + P_{\text{loss}}
\]

where \(V_{\text{dc}}\) is the DC voltage of the DC current, \(r_1\) is the equivalent impedance of the transmission line from the wind farm to the sending AC grid. \(X_{\text{dc}}\) is the line reactance of the transmission line from the wind farm to the sending AC grid. \(P_{\text{loss}}\) is the line loss of the wind farm.

The power absorbed by the rectifier station is provided by the thermal power plant, wind farms and AC filters, which can be expressed as:

\[
\begin{align*}
P_{\text{rs}} &= P_{\text{tp}} + \sum_{i=1}^{n} (P_{\text{wf}i} - P_{\text{ll}i}) + P_{\text{acf}} \\
Q_{\text{rs}} &= Q_{\text{tp}} + \sum_{i=1}^{n} (Q_{\text{wf}i} - Q_{\text{ll}i}) + Q_{\text{acf}}
\end{align*}
\]

where \(P_{\text{rs}}\) and \(Q_{\text{rs}}\) are the active power and reactive power absorbed by the rectifier station. \(n\) is the number of wind farms on the sending AC grid. \(i\) is the number of the wind farm. \(P_{\text{tp}}\) and \(Q_{\text{tp}}\) are the active power and reactive power of the thermal power plant. \(P_{\text{wf}i}\) and \(Q_{\text{wf}i}\) are the active power and reactive power of the wind farm. \(P_{\text{acf}}\) and \(Q_{\text{acf}}\) are the active power and reactive power of the AC filters. Due to the line reactance of the transmission line from the wind farm to the sending AC bus, the active power and reactive power of the wind farm are partly absorbed by the transmission line, which is called line loss of the wind farm. \(P_{\text{ll}}\) and \(Q_{\text{ll}}\) are the line loss of the wind farm.

The line loss of the wind farm can be expressed as:

\[
P_{\text{ll}i} + jQ_{\text{ll}i} = \left(\frac{P_{\text{ll}i} + jQ_{\text{ll}i}}{U_s}ight)^2 Z_{\text{w}i}
\]

where \(U_s\) is the bus voltage of the sending AC grid. \(Z_{\text{w}i}\) is the is the equivalent impedance of the transmission line from the wind farm to the sending AC bus.

According to (2), the ratio of the line loss of a wind farm to the output power of the wind farm can be expressed as \((P_{\text{ll}i} + jQ_{\text{ll}i})Z_{\text{w}i} / U_s^2\). According to Table I, the rated value of \(U_s\) is 500kV, the output power of a single wind farm does not exceed 500MW, and the line impedance of the wind farm

![Topological structure diagram of the LCC-HVDC system.](image1.png)

**FIGURE 1.** Topological structure diagram of the LCC-HVDC system.

![Signals of the LCC-HVDC system under commutation failure.](image2.png)

**FIGURE 2.** Signals of the LCC-HVDC system under commutation failure.

Fig. 2 shows the signals of the LCC-HVDC system under commutation failure. The mechanism of the voltage fluctuation of the sending AC grid under the commutation failure is given in [6]. The detailed parameters of the LCC-HVDC system are listed in Table I. A single-phase fault occurred in the receiving AC grid at 2s, which caused a commutation failure in the LCC-HVDC system. When the commutation failure occurs in the LCC-HVDC system, the DC voltage of the LCC-HVDC system drops to 0 then returns to the rated value. The DC current first increases to 2.04pu, then drops to 0 and finally returns to the rated value. The reactive power absorbed by the rectifier station due to the fluctuation of the DC voltage and current first increases and then decreases. Therefore, the voltage amplitude of the sending AC grid to first decrease to 0.25pu and then increase to 1.32pu. The overvoltage of the sending AC grid will threaten the normal operation of the wind farms on the sending AC grid. It is necessary to quantitatively analyze the influence of the power characteristics of the wind farms on the voltage of the sending AC grid.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{\text{wth}})</td>
<td>Transmission capacity</td>
<td>1600 MW</td>
</tr>
<tr>
<td>(U_{\text{wth}})</td>
<td>Rated DC voltage</td>
<td>±500 kV</td>
</tr>
<tr>
<td>(U_{\text{wa}})</td>
<td>Rated voltage of sending AC bus</td>
<td>500 kV</td>
</tr>
<tr>
<td>(U_{\text{wa}})</td>
<td>Rated voltage of receiving AC bus</td>
<td>500 kV</td>
</tr>
<tr>
<td>(U_{\text{tp}})</td>
<td>Equivalent internal voltage of the thermal power plant</td>
<td>540 kV</td>
</tr>
<tr>
<td>(X_{\text{tp}})</td>
<td>Equivalent internal impedance of the thermal power plant</td>
<td>23+160 Ω</td>
</tr>
<tr>
<td>(Q_{\text{tp}})</td>
<td>Rated capacity of the AC filter</td>
<td>540 Mvar</td>
</tr>
</tbody>
</table>

The line loss of the wind farm can be expressed as:

\[
P_{\text{ll}i} + jQ_{\text{ll}i} = \left(\frac{P_{\text{ll}i} + jQ_{\text{ll}i}}{U_s}ight)^2 Z_{\text{w}i}
\]
does not exceed 100Ω. \((P_{\text{af}} + jQ_{\text{af}})Z'_{\text{af}} \ll U_{i}^{2}\) can be obtained, that is, the line loss of a wind farm is negligible compared to the output power of the wind farm.

![Diagram](image)

**FIGURE 3. Structure diagram of the 310Mvar AC filter.**

Fig. 3 shows the 310Mvar AC filter used in the converter station of the LINGSHAO HVDC system in China. Its tuning frequency is 600Hz and 1200Hz. The parameters are given as follows, \(C_{1}=3.744 \mu \text{F}, L_{1}=8.172 \text{mH}, C_{2}=7.083 \mu \text{F}, L_{2}=5.587 \text{mH}, R_{1}=270 \Omega\).

The impedance of the AC filter can be expressed as:

\[
Z_{\text{af}} = \frac{1}{j\omega_{0}C_{1}} + \frac{1}{\frac{1}{R_{1}} + \frac{1}{\frac{1}{j\omega_{0}L_{1}(1-\omega_{0}^{2}C_{2}L_{2})}+L_{2}}} \tag{3}
\]

where \(\omega_{0}\) is the angular frequency of the grid.

According to (3), the impedance of the 310Mvar AC filter is 7.03×10^{-7}-j850.2Ω. Therefore, the active power \(P_{\text{af}}\) of the AC filter is negligible compared to the reactive power \(Q_{\text{af}}\) of the AC filter. (1) can be rewritten as:

\[
\begin{align*}
    P_{n} & = P_{p} + \sum_{i=1}^{n} P_{i}\text{af} \\
    Q_{n} & = Q_{p} + \sum_{i=1}^{n} Q_{i}\text{af} + Q_{\text{af}}
\end{align*} \tag{4}
\]

The duration of a commutation failure fault is hundreds of milliseconds, and the inertia time constant of a synchronous generator in a thermal power plant is usually a few minutes, so the internal potential change of the synchronous generator during the fault can be ignored. According to the classic model of the synchronous generator, the voltage amplitude of the sending AC bus can be expressed as [6]:

\[
U_{s} = U_{p} - \frac{R_{p}}{U_{p}} P_{p} - \frac{X_{p}}{U_{p}} Q_{p} \tag{5}
\]

where \(U_{ip}\) is the equivalent internal voltage of the thermal power plant. \(R_{p}\) is the equivalent internal resistance of the thermal power plant. \(X_{p}\) is the equivalent internal reactance of the thermal power plant.

Since the sub-transient reactance of the synchronous generator in the thermal power plant is much larger than the winding damping [18], the reactive power of the thermal power plant is the main factor that affects the bus voltage of the sending AC grid.

When the DC current of the rectifier station drops to zero, the power absorbed by the rectifier station is 0, the voltage amplitude of the sending AC grid reaches the maximum value [6]. At this time, the thermal power plants, wind farms and AC filters on the sending AC grid reach a power balance. The change in the maximum value of the AC bus overvoltage of the sending AC grid can be expressed as:

\[
\Delta U_{s} = -\frac{X_{p}}{U_{p}} \Delta Q_{p} = \frac{X_{p}}{U_{p}} U_{0} \left(\sum_{i=1}^{n} \Delta Q_{i}\text{af} + \Delta Q_{\text{af}}\right) \tag{6}
\]

Since the commutation failure fault is recoverable in a short time, the AC filters installed in the sending AC system are not allowed to be removed during commutation failure [5]. The change of the reactive power of the AC filter under commutation failure can be expressed as:

\[
\Delta Q_{\text{af}} = -\frac{2\Delta U_{s}}{U_{0}} Q_{\text{af}0} \tag{7}
\]

where \(U_{0}\) is the bus voltage of the sending AC grid before the fault. \(Q_{\text{af}0}\) is the reactive power of the AC filter before the fault.

By substituting (7) into (6), the change in the maximum value of the AC bus overvoltage of the sending AC grid can be expressed as:

\[
\Delta U_{s} = -\frac{X_{p}}{U_{p}} U_{0} \left(\sum_{i=1}^{n} \Delta Q_{i}\text{af} - \frac{2\Delta U_{s}}{U_{0}} Q_{\text{af}0}\right) \tag{8}
\]

According to (8), the influence of the reactive power of the wind farm on the overvoltage of the sending AC grid under commutation failure can be analyzed. The influence of the reactive power of the wind farm on the bus voltage of the sending AC grid can be expressed as:

\[
\Delta U_{s} = -\frac{X_{p}}{U_{p}} U_{0} \left(\sum_{i=1}^{n} \Delta Q_{i}\text{af} - \frac{2\Delta U_{s}}{U_{0}} U_{0} Q_{\text{af}0}\right) \tag{9}
\]

According to (9), the overvoltage of the sending AC grid under commutation failure can be suppressed by increasing the capacity of wind farms to absorb reactive power.

The commutation failure of the LCC-HVDC system is caused by the thyristor shoot-through in the inverter station. There are various reasons that cause the thyristor shoot-through, e.g., the loss of trigger pulse and the faults in the receiving AC grid. The shoot-through time of the thyristor is mainly affected by the parameters of the LCC-HVDC system. The shoot-through time of the thyristor caused by different faults is slightly different. Therefore, the commutation failure caused by different faults has little effect on the voltage in the sending AC grid.
Fig. 3 shows the voltage amplitude of the sending AC grid under commutation failure caused by different faults.

![Figure 4: Amplitude of the grid voltage under commutation failure caused by different faults.](image)

According to Fig 4, the voltage amplitude of the sending AC grid is very similar under commutation failure caused by the single-phase fault, phase to phase fault, three-phase fault and inductive fault at inverter’s end. The commutation failures caused by different faults in receiving AC grid has little effect on the voltage in the sending AC grid.

**B. RESTRICTION RELATIONSHIP BETWEEN REACTIVE POWER AND ACTIVE POWER OF WIND FARM**

A mathematical model of the wind farm considering the restriction of active power by the wind power conditions is proposed in this part B to calculate the power modulation range of the DFIG-based wind farm and the PMSG-based wind farm. There are many researches on analyzing the power modulation range of the wind turbine, such as [19]-[21]. [19] and [20] analyzed the power modulation range of the DFIG, and [21] analyzed the power modulation range of the PMSG. However, the existing mathematical models lack a comparative analysis of the power modulation range of the two types of wind turbines under overvoltage.

The main factors that restrict the active power modulation capability of a wind turbine have two constraints, i.e., the allowable maximum speed of rotor and the maximum active power capacity determined by the turbine or converter. The maximum speed of the rotor of a wind turbine is determined by the local wind power conditions of the wind farm. The maximum active power capacity is determined by the installed capacity of the wind turbine. According to the design principles of wind turbines, when the rotor reaches the maximum speed, the active output power of the wind turbine will not exceed the limit of the converter capacity. A wind farm is composed of several wind turbines, and the active power limit of the wind farm can be expressed as:

\[
\begin{align*}
    P_{\text{ref}}^i &\leq P_{\text{max}}^i \leq S_{\text{ref}}^i , i = 1,2,\ldots,n
\end{align*}
\]  

where \(P_{\text{max}}^i\) is the maximum active power of the wind farm determined by the wind condition. \(S_{\text{ref}}^i\) is the capacity of the wind farm.

The reactive power of wind turbines does not need to change the rotational kinetic energy of the turbines, so its regulating ability is not limited by the speed range of the wind turbines, but only by the capacity of the converter and the wind turbines. Wind turbines are mainly divided into direct drive turbines using permanent magnet synchronous generators (PMSGs) and doubly-fed turbines using double-fed induction generators (DFIGs) [22]. The capacity limits of PMSGs and DFIGs are the same, and the capacity limit of a wind farm can be expressed as:

\[
\sqrt{P_{\text{ref}}^i + Q_{\text{ref}}^i} \leq S_{\text{ref}}^i , i = 1,2,\ldots,n
\]

where \(P_{\text{ref}}^i\) and \(Q_{\text{ref}}^i\) are the limits of the reactive power absorbed by the grid side converter (GSC) and the active power output by the PMSG. The reactive power absorption capability of a PMSG is limited by the capacity of the GSC and the active power of the PMSG. The active power of a PMSG is limited by the maximum active power output, which is determined by the working conditions of the wind farm. Fig. 5 shows the power modulation range of a PMSG.

![Figure 5: Power modulation range of a PMSG.](image)

The converter capacity limits of PMSGs and DFIGs are different. The reactive power output by the grid side converter (GSC) is the reactive power output by the PMSG. The reactive power absorption capability of a PMSG is limited by the capacity of the GSC and the active power of the PMSG. The active power of a PMSG is limited by the maximum active power output, which is determined by the working conditions of the wind farm. Fig. 5 shows the power modulation range of a PMSG.

\[
\sqrt{I_{\text{rd}}^2 + I_{\text{rq}}^2} \leq I_{\text{r max}}
\]

where \(I_{\text{rd}}\) is the d-axis component of the rotor current. \(I_{\text{rq}}\) is the q-axis component of the rotor current. \(I_{\text{r max}}\) is the maximum value of the rotor current.

The relationship between the rotor current and the power of the DFIG can be expressed as [20]:

\[
\begin{align*}
    I_{\text{rd}} &= \frac{2P_{\text{DFIG}}}{3U_L L_m} \\
    I_{\text{rq}} &= \frac{-2Q_{\text{DFIG}}}{3U_L L_m} \frac{U_L}{L_m}
\end{align*}
\]
where \( P_{DFIG} \) and \( Q_{DFIG} \) are the active power and reactive power of the DFIG. \( L_s \) is the inductance of stator windings. \( L_m \) is the mutual inductance. \( U_g \) is the grid voltage.

### Table II
PARAMETERS OF THE DFIG

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_{uf} )</td>
<td>Rated stator voltage</td>
<td>690 V</td>
</tr>
<tr>
<td>( P_{uf} )</td>
<td>Rated power</td>
<td>2 MW</td>
</tr>
<tr>
<td>( R_s )</td>
<td>Stator resistance</td>
<td>0.0018 ( \Omega )</td>
</tr>
<tr>
<td>( R_r )</td>
<td>Rotor resistance</td>
<td>0.0044 ( \Omega )</td>
</tr>
<tr>
<td>( L_s )</td>
<td>Inductance of stator windings</td>
<td>3.47 mH</td>
</tr>
<tr>
<td>( L_m )</td>
<td>Inductance of rotor windings</td>
<td>3.77 mH</td>
</tr>
<tr>
<td>( I_{ms} )</td>
<td>Mutual inductance</td>
<td>3.40 mH</td>
</tr>
<tr>
<td>( V_{dref} )</td>
<td>Rated DC voltage of RSC</td>
<td>1050 V</td>
</tr>
<tr>
<td>( \omega_s )</td>
<td>Rated rotor speed</td>
<td>120\pi \text{ rad/s}</td>
</tr>
</tbody>
</table>

According to (10), (11) and (12), the reactive power absorption capability of a DFIG is limited by the maximum rotor current and the capacity of the DFIG. Similar to PMSG, the active power of a DFIG is limited by the maximum active power output which is determined by the working conditions of the wind farm. Fig. 6 shows the power modulation range of a DFIG. The detailed parameters of the DFIG are listed in Table II.

![Power modulation range of a DFIG](image)

**FIGURE 6.** Power modulation range of a DFIG.

According to Fig.6, it can be seen that the main limitation for the DFIG to send reactive power to the grid is the capacity of the RSC and the main limitation for the DFIG to absorb reactive power from the grid is the capacity of the generator [20]. The reactive power absorption capacity of a wind farm composed of DFIGs is the same as a wind farm composed of PMSGs, which can be expressed as:

\[
Q_{nf}^i \geq -\sqrt{S_{nf}^i - P_{nf}^i}, i = 1,2,\ldots,n \tag{14}
\]

According to (11) and (14), whether it is a wind farm composed of DFIGs or a wind farm composed of PMSGs, its reactive power absorption capacity is mainly limited by the active power and capacity of the wind farm. Adjusting the active power distribution of wind farms on the sending AC grid can increase the total reactive power absorption capacity of the wind farms.

### C. OPTIMAL DISTRIBUTION METHOD FOR WIND FARMS TO IMPROVE FRT CAPABILITY OF THE LCC-HVDC SYSTEM UNDER COMMUTATION FAILURE

According to the technical rule for connecting wind farm to power system, when the grid voltage exceeds 1.3 pu, the wind farm is at risk of being separated from the grid [7]. In order to improve the FRT capability of the LCC-HVDC system under commutation failure, it is necessary to suppress the overvoltage of the sending AC grid under commutation failure.

According to (9), the overvoltage of the sending AC grid under commutation failure can be suppressed by increasing the capacity of wind farms to absorb reactive power. According to Fig. 5 and Fig. 6, it can be seen that the capacity of a wind farm is the main factor limiting the absorption of reactive power by the wind farm. The reactive power absorption capacity \( Q_{nf,all} \) that can be absorbed by the wind farms on the sending AC grid can be expressed as:

\[
Q_{nf,all}(P_{nf,1}^i, P_{nf,2}^i, \ldots, P_{nf,n}^i) = \sum_{i=1}^{n} \sqrt{(S_{nf}^i)^2 - (P_{nf}^i)^2} \tag{15}
\]

During periods of low load (such as 1:00-4:00 at night), the active power output by the wind farm on the sending AC grid is limited [23]. The optimal method to improve the FRT capability of the LCC-HVDC system should maximize the reactive power absorption capacity \( Q_{nf,all} \) absorbed by the wind farms on the sending AC grid. The boundary condition of the active power of the wind farm can be expressed as:

\[
\sum_{i=1}^{n} P_{nf}^i = P_{wind} \tag{16}
\]

\[0 \leq P_{nf}^i \leq P_{nf,\text{max}}, i = 1,2,\ldots,n\]

where \( P_{wind} \) is the maximum wind power capacity of the LCC-HVDC system.

\( Q_{nf,all} \) in (15) is a convex function and the boundary conditions in (16) are linearly independent, which should satisfy the Kuhn-Tucker condition. Therefore, the Kuhn-Tucker multiplier \( \lambda \) can be introduced to construct the function \( F \), which can be expressed as:

\[
F(P_{nf,1}^i, P_{nf,2}^i, \ldots, P_{nf,n}^i, \lambda_{1}, \lambda_{2}, \ldots, \lambda_{n}, g_1, \ldots, g_n) = \sum_{i=1}^{n} \sqrt{(S_{nf}^i)^2 - (P_{nf}^i)^2} + \lambda_{i}(\sum_{i=1}^{n} P_{nf}^i - P_{wind}) + \sum_{i=1}^{n} \lambda_i(P_{nf,\text{max}} - P_{nf}^i - g_i) \tag{17}
\]

The maximum point of \( Q_{nf,all} \), that is, the Kuhn-Tucker point of function \( F \), can be expressed as:
The effective solution of (18) is the optimal power distribution method of wind farm on the sending AC grid. The flow chart of the optimal power distribution method is given in Fig. 7.

**FIGURE 7. Flow chart of the optimal power distribution method.**

### III. CASE ANALYSIS AND SIMULATION VERIFICATION

As shown in Fig. 1, several wind farms are connected to the sending AC grid to transmit electric energy through an LCC-HVDC system.

During the high voltage ride-through process of wind turbines, when the grid voltage is higher than the threshold, the wind turbines will absorb reactive power at their maximum capacity. In order to reflect the effectiveness of the optimal power distribution method, the wind farm in this paper uses the maximum reactive power absorption capacity as the reactive power command during the peak overvoltage stage of the sending AC grid under commutation failure.

In order to prove the effectiveness and universality of the proposed optimal power distribution method, two cases are designed in this section for analysis and a simulation model was built based on Matlab/Simulink to verify the proposed power distribution method.

#### A. CASE 1

In the Case 1, it is assumed that $n=10$, in which ten wind farms are installed on the sending AC grid. During the low load periods of the receiving AC grid, the transmission power of the LCC-HVDC system is limited to 1600MW. Some thermal power plants on the sending AC grid need to be connected to the grid to provide voltage support and frequency support [24]. Taking into account the necessary thermal power plant capacity, the maximum wind power capacity that the LCC-HVDC system can transmit is limited to 1200MW.

The capacity and the wind power conditions of the wind farms on sending AC grid are listed in Table III. The wind farms numbered WF1 to WF5 are composed of PMSGs and the Wind farms numbered WF6 to WF10 are composed of DFIGs. According to Table III, the maximum active power of the wind farms on the sending AC grid is 1650MW, which exceeds the wind power capacity of the LCC-HVDC system.

The power of the wind farm before adopting the optimal power distribution method is distributed as follows: the generated power of wind farms on the sending AC grid is reduced proportionally until the generated power of all wind farms meets the transmission capacity requirements of the LCC-HVDC system. The active power of the wind farm before optimization is listed in Table III. According to the rated capacity and active power of each wind farm, the reactive power absorption capacity of each wind farm can be calculated, which is listed in Table III. According to (15), the reactive power absorption capacity of the wind farms before adopting the optimal power distribution method is 1525 Mvar.

#### TABLE III

<table>
<thead>
<tr>
<th>Number $i$ of Wind farm</th>
<th>Capacity $S_{wf}^i$ of Wind Farm (MW)</th>
<th>Maximum Active Power $P_{max}^i$ (MW)</th>
<th>Active Power $P_{wfi}$ (MW)</th>
<th>Reactive Power Capacity $Q_{wf}^i$ (Mvar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WF1</td>
<td>170</td>
<td>170</td>
<td>123.6</td>
<td>116.7</td>
</tr>
<tr>
<td>WF2</td>
<td>120</td>
<td>120</td>
<td>87.3</td>
<td>82.3</td>
</tr>
<tr>
<td>WF3</td>
<td>200</td>
<td>200</td>
<td>145.6</td>
<td>137.1</td>
</tr>
<tr>
<td>WF4</td>
<td>240</td>
<td>170</td>
<td>123.6</td>
<td>205.7</td>
</tr>
<tr>
<td>WF5</td>
<td>220</td>
<td>220</td>
<td>160</td>
<td>151.0</td>
</tr>
<tr>
<td>WF6</td>
<td>120</td>
<td>120</td>
<td>87.3</td>
<td>82.3</td>
</tr>
<tr>
<td>WF7</td>
<td>380</td>
<td>180</td>
<td>130.9</td>
<td>356.7</td>
</tr>
<tr>
<td>WF8</td>
<td>170</td>
<td>170</td>
<td>123.6</td>
<td>116.7</td>
</tr>
<tr>
<td>WF9</td>
<td>240</td>
<td>240</td>
<td>174.5</td>
<td>164.8</td>
</tr>
<tr>
<td>WF10</td>
<td>120</td>
<td>60</td>
<td>43.6</td>
<td>111.8</td>
</tr>
</tbody>
</table>

By substituting the capacity of the wind farm, the maximum active power of the wind farm and the maximum wind power capacity of the LCC-HVDC system into equation (18), the optimal power distribution method of wind farm is given in Table IV. The reactive power absorption capacity of the wind farms on the sending AC grid using the proposed optimal power distribution method reaches the maximum value of 1665 Mvar. The proposed optimal power distribution method increases the reactive power absorption capacity of wind farms in the transmission grid by 140 Mvar. The increased reactive power absorption capacity of wind farms can suppress the overvoltage under commutation failure and improve the FRT capability of the LCC-HVDC system.

According to the topology structure of the LCC-HVDC system in Fig. 1, a 500kV LCC-HVDC system simulation model was built based on Matlab/Simulink to verify the effectiveness of the proposed optimal power distribution method. The detailed parameters of the 500kV LCC-HVDC system are given in the Table I in section II.
In the simulation model, there are ten wind farms connected to the sending AC grid, whose capacity configuration parameters are given in Table III. A wind farm is usually composed of multiple wind turbines of the same type. It is a feasible way to use an aggregation model to equivalence a wind farm [25]. Research indicates that the per-unit parameters of a wind farm aggregation model are equal to the per-unit parameters of a wind turbine [25][26].

Considering that the wind farms in the case are composed of different types of wind turbines, the aggregation models of the wind farms numbered WF1 to WF5 use the parameters of a 1.5MW PMSG. The detailed parameters of the PMSG-based aggregation model are given in appendix. In the same way, the aggregation models of the wind farms numbered WF6 to WF10 use the parameters of a 2MW DFIG. The detailed parameters of the DFIG-based aggregation model are given in appendix.

Fig. 8 shows the bus voltage of the sending ac grid under commutation failure without using the optimal power distribution method, which is consistent with the result in Fig.2.

According to Fig. 10, it can be seen that the maximum overvoltage of the sending AC grid is 1.32pu before adopting proposed optimal method. However, the maximum overvoltage of the sending AC grid is 1.24pu after adopting proposed optimal method. The proposed optimal power distribution method has increased the reactive power absorption capacity of wind turbines on the sending AC grid by 140 Mvar. By substituting the additional 140Mvar reactive power absorbed by the wind farm and the parameters of the sending AC grid in Table I into (9), the bus voltage of the sending AC grid can be calculated. It can be found that the bus voltage of sending AC grid is reduced by 41.5kV, i.e., 0.083 pu. The accuracy of the mathematical model in part A of section II has been verified.

If the wind turbine adopts the control strategy to reduce active power under faults, the reactive power absorbed can be further increased, thereby suppressing the overvoltage of the sending AC grid. [21] proposed an active power limiting
strategy for the PMSG and [17] is proposed an active power limiting strategy for the DFIG. Since the commutation failure lasts for about 200ms, the control strategy of reducing active power will cause the active power output of the wind farm to fluctuate rapidly within 200ms, which may affect the frequency stability of the sending AC grid. The optimal power distribution strategy can maintain the stable output of the active power of the wind farm, which is conducive to the stable frequency of the sending AC grid.

The proposed optimal power distribution method can effectively eliminate the risk of separation of the wind farms from the grid on the sending AC grid by suppressing the maximum overvoltage to below 1.3pu under commutation failure. Furthermore, it is proved that the proposed optimal power distribution method can effectively improve the FRT capability of the LCC-HVDC system under commutation failure.

B. CASE 2

In order to verify the universality of the proposed optimal power distribution method, Case 2 under the same hardware parameters as Case 1 is designed.

The transmission power of the LCC-HVDC system in Case 2 is further limited to 1200MW. Same as Case 1, it is necessary to reserve capacity for the thermal power plant in sending AC grid. Therefore, the maximum wind power capacity that the LCC-HVDC system can transmit is limited to 900MW.

Since Case 2 and Case 1 adopt the same parameters of the wind farms, the installed capacity of the wind farms and the type of the wind farms remain unchanged. However, the wind conditions of each wind farm on the sending AC grid are changed, the maximum active power of the wind farms is listed in Table V. According to Table V, the maximum active power of the wind farm on the sending AC grid is 1350MW, which exceeds the wind power capacity of the LCC-HVDC system.

| TABLE V | THE ACTIVE POWER OF THE WIND FARMS WITHOUT THE PROPOSED OPTIMAL POWER DISTRIBUTION METHOD IN CASE 2 |
|---|---|---|---|---|---|
| Number i of Wind farm | Capacity $S_{i,c}$ of Wind Farm (MW) | Maximum Active Power $P_{i,m}^c$ (MW) | Active Power $P_{i,c}^c$ (MW) | Reactive Power Absorption Capacity (Mvar) |
| WF1 | 170 | 170 | 113.4 | 126.6 |
| WF2 | 120 | 120 | 80 | 89.4 |
| WF3 | 200 | 100 | 66.7 | 188.5 |
| WF4 | 240 | 100 | 66.7 | 230.5 |
| WF5 | 220 | 120 | 80 | 204.9 |
| WF6 | 120 | 80 | 53.3 | 91.4 |
| WF7 | 380 | 380 | 253.3 | 193.2 |
| WF8 | 170 | 50 | 33.3 | 166.7 |
| WF9 | 240 | 110 | 73.3 | 228.5 |
| WF10 | 120 | 120 | 80 | 89.4 |

The power of the wind farm before adopting the optimal power distribution method is distributed as follows: the generated power of wind farms on the sending AC grid is reduced proportionally until the generated power of all wind farms meets the transmission capacity requirements of the LCC-HVDC system. The active power and reactive power absorption capacity of the wind farms before optimization are listed in Table V. According to (15), the reactive power absorption capacity of the wind farms before adopting the optimal power distribution method is 1609 Mvar.

By substituting the capacity of the wind farm, the maximum active power of the wind farm and the maximum wind power capacity of the LCC-HVDC system into equation (18), the optimal power distribution method of the wind farms is given in Table VI. The reactive power absorption capacity of the wind farms on the sending AC grid using the proposed optimal method reaches the maximum value of 1710 Mvar. The proposed optimal power distribution method increases the reactive power absorption capacity of wind farms in the transmission grid by 101 Mvar. The increased reactive power absorption capacity of wind farms can suppress the overvoltage of sending AC grid and improve the FRT capability of the LCC-HVDC system under commutation failure.

| TABLE VI | OPTIMAL POWER DISTRIBUTION METHOD FOR WIND FARMS IN CASE 2 |
|---|---|---|---|---|
| Number i of Wind farm | Maximum Active Power $P_{i,m}^c$ (MW) | Distributed Active Power $P_{i,c}^c$ (MW) | Reactive Power Absorption Capacity (Mvar) |
| WF1 | 170 | 81.9 | 149.0 |
| WF2 | 120 | 57.7 | 105.2 |
| WF3 | 100 | 96.2 | 175.3 |
| WF4 | 100 | 100 | 218.2 |
| WF5 | 120 | 105.9 | 192.8 |
| WF6 | 80 | 57.7 | 105.2 |
| WF7 | 380 | 182.9 | 333.1 |
| WF8 | 50 | 50 | 162.5 |
| WF9 | 110 | 110 | 213.3 |
| WF10 | 120 | 57.7 | 105.2 |

Since the parameters of the wind farms are unchanged, the 500kV LCC-HVDC system simulation model in Case 1 is used to verify the effectiveness of the proposed optimal power distribution method. Fig 11 shows the voltage amplitudes of the sending AC grid before and after the proposed optimal power distribution method in case 2.
serving AC grid has been increased from 0.04 pu to 0.1 pu, which is increased to 2.5 times. The proposed optimal power distribution method can effectively improve the FRT capability of the LCC-HVDC system under commutation failure.

The proposed optimal power distribution method has increased the reactive power absorption capacity of wind turbines on the sending AC grid by 101 Mvar in case 2. By substituting the additional 101 Mvar reactive power absorbed by the wind farm and the parameters of the sending AC grid in Table I into (9), the bus voltage of the sending AC grid can be calculated. It can be found that the bus voltage of sending grid is reduced by 29.9 kV, i.e., 0.060 pu.

In different cases, the accuracy of the mathematical model in section II has been verified. The proposed optimal power distribution method can effectively suppress the overvoltage of sending AC grid and improve the FRT capability of the LCC-HVDC system under commutation failure.

IV. CONCLUSION
This paper proposes an optimal power distribution method for the wind farms connected to the sending AC grid of the LCC-HVDC system to improve the FRT capability of the LCC-HVDC system under commutation failure. A mathematical model is established to analyze the influence of the power distribution of wind farms on the overvoltage of the sending AC grid. The optimal power distribution method considering the wind power conditions of the wind farms is proposed to maximize the reactive power absorption capacity, which can suppress the overvoltage of the sending AC grid and improve the FRT capability of the LCC-HVDC system under commutation failure. Two cases are designed to verify the effectiveness of the proposed optimal power distribution method.

APPENDIX
The following are the parameters of the PMSG-based aggregation model.

1. Rated voltage: $V_{fmin} = 690$ V
2. Rated DC voltage of GSC: $V_{dc} = 1200$ V
3. Filter inductance in LC filter: $L_f = 0.0099$ pu
4. Filter capacitance in LC filter: $C_f = 1.8550$ pu
5. Filter resistance in LC filter: $R_f = 0.0315$ pu

The following are the parameters of the DFIG-based aggregation model.

1. Rated stator voltage: $V_{s} = 690$ V
2. Stator resistance: $R_s = 0.0066$ pu
3. Rotor resistance: $R_r = 0.0161$ pu
4. Inductance of stator windings: $L_s = 3.9945$ pu
5. Inductance of rotor windings: $L_r = 4.312$ pu
6. Mutual inductance: $L_m = 3.9124$ pu
7. Rated DC voltage of RSC: $V_{dcl} = 1050$ V
8. Rated rotor speed: $\omega_r = 120$ rad/s

REFERENCES


