Reactive Power Control Strategy of DFIG Wind Farms for Regulating Voltage of Power Grid

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Abstract—**If a wind farm is weakly connected to a power grid, then the voltage of the connection point fluctuates frequently due to the changeable wind speed. The active and reactive power of a doubly-fed induction generator (DFIG) can be decoupling controlled and the grid-side converter (GSC) of a DFIG can also generate some reactive power by adjusting the power factor, thus a DFIG can be considered as a reactive power resource to stabilize the voltage of the connection bus. Based on the power relationship of a DFIG, the up and down reactive power limitations of DFIG stator and GSC are analyzed. Then a reactive power control strategy of a DFIG wind farm is proposed, in which, a certain number of DFIGs are selected to support reactive power to the power grid when the voltage of the connection point drops. The control strategy aims at bringing the reactive power capability of DFIG into play and cutting down the investments in the reactive power compensation devices which are used less. The simulation model of a grid-connected DFIG wind farm is developed on the PSCAD/EMTDC platform, and the simulation results demonstrate the effectiveness of the control strategy proposed.**

Index Terms--**Doubly-fed induction generator (DFIG); reactive power control; voltage control; power limitation.**

I. INTRODUCTION

Nowadays more and more wind farms are connected into the power grid. Long-distance transmission lines are usually required for the connection because most wind farms are located at the remote areas or off shores. The output active power of wind farms is variable and intermittent due to the changeable wind speed, which threats the voltage stability of local power grids. More reactive power is demanded to maintain the voltage when it drops. Since a wind farm is composed of many wind turbines, the operation and control modes of the wind turbines have a great impact on the voltage stability of local power grids. The doubly-fed induction generator (DFIG) is widely used in wind farms because it has many advantages, one of which is the decoupled control of active and reactive power [1]. Besides, both the stator and the grid-side converter (GSC) of a DFIG can inject reactive power into the grid to help to maintain the fluctuant voltage [2][3]. As mentioned, the voltage of a weakly-connected power grid to wind farms is usually unstable, thus taking the reactive power from DFIGs into account will make the compensation more flexible.

There are mainly two reactive power control modes for a DFIG wind turbine, one is power factor control mode and the other is voltage control mode [4]. Many papers have focused on the reactive power characteristics of DFIG wind turbine. The research contents cover the dynamic reactive power limits of doubly-fed wind turbine, the use of reactive power regulation capability to improve the local voltage stability, and the reactive power support for the grid [5]. The voltage stability of power system is mainly dependent on the balance of reactive power, as a result, the doubly-fed wind farm should be equipped with corresponding voltage control schemes according to the reactive power compensation situation [6]-[7]. Based on zoning plans, reference [8] proposed the automatic voltage control strategy of wind farm, which combined the DFIG voltage control with other voltage regulation measures such as switching capacitors. According to the optimal secondary voltage control theory, reference [9] suggested that the reactive power regulation capability would be better played when the key node voltage was controlled. These papers take all the wind turbines in the wind farm into account when allocating the reactive power, which may not only increases the power loss of wind turbines but also makes the dispatch and control of the total wind farm more difficult.

This paper proposes a more flexible reactive power control strategy. The up and down limitations on the reactive power of a DFIG are deduced based on the power relationship. When the voltage of the connection bus drops due to some load disturbances in the power grid, a certain number of DFIG wind turbines are selected according to the up and down limitations to inject the demanded reactive power into the grid, helping to recover the voltage. Not all the wind turbines are involved in this control strategy, the number is dependent on the reactive power needed by the power grid and is determined dynamically. Finally, the proposed strategy is verified by simulations on the PSCAD/EMTDC platform.

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II. REACTIVE POWER CHARACTERISTIC OF A DFIG WIND TURBINE

A. Power Relationship of a DFIG Wind Turbine

The topology of a DFIG is shown in Fig. 1. The stator of a DFIG is connected to the power grid directly, while the rotor is connected to the grid through two back-to-back pulse width modulation (PWM) converters, i.e. rotor-side converter and grid-side converter. The grid-side converter usually works at the unity power factor of 1 and is in charge of maintaining a constant DC-link voltage for the rotor-side converter. The decoupling control of active and reactive power of the DFIG is achieved by adjusting the rotor's current and voltage through the rotor-side converter.

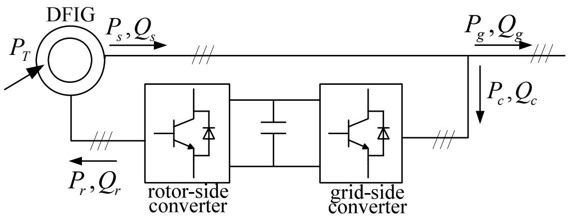


Figure 1. Topology of a DFIG

In Fig. 1, P_T is the input mechanical power from the wind turbine, P_s and Q_s are the output active and reactive power generated by the DFIG, P_c and Q_c are the active and reactive power to the grid-side converter from the DFIG, P_g and Q_g are the active and reactive power to the grid from the DFIG, P_r and Q_r are the active and reactive power to the rotor winding from the rotor-side converter. Assuming that the input mechanical power is completely converted into the electromagnetic power, the power relationship of DFIG can be presented as:

$$P_T = P_s - P_r \tag{1}$$

The difference between the stator speed and the synchronous speed results in the slip power of the rotor, which is named as the rotor power P_r. Therefore the power relationship can also be expressed as:

$$\begin{cases} P_s = P_T/(1-s) \\ P_r = sP_T/(1-s) \end{cases} \tag{2}$$

B. Reactive Power Limitations of the Grid-side Converter

The rotor-side and grid-side converters only transfer active power, while the reactive power Q_c and Q_r are decoupled. If the power loss is neglected, there is $P_c = P_r$. Since the grid-side converter usually works at the unity power factor of 1, there is $Q_c = 0$. However, Q_r is divided into two parts, one part flows into the rotor, and the other part is transferred to the stator by a certain percentage (slip ratio). Therefore, the capacity of the rotor-side converter is larger than that of the grid-side converter. As a result, when analyzing the reactive power limitations of the grid-side converter, only the capacity of itself is considered.

For a low wind speed, the grid-side converter does not make full use of its capacity. When the grid requires extra reactive power, the grid-side converter can be adjusted into a non-unity power factor to meet the requirement. Assuming the maximum capacity of the grid-side converter is $S_{c\max}$, there is $P_c^2 + Q_c^2 \le S_{c\max}^2$. The reactive power that the grid-side converter can generate or absorb is presented as:

$$-\sqrt{S_{c\max}^2 - P_c^2} \le Q_c \le \sqrt{S_{c\max}^2 - P_c^2} \tag{3}$$

Combining (2) and (3), the reactive power limitations of the grid-side converter can be illustrated as:

$$\begin{cases} Q_{c\max} = \sqrt{S_{c\max}^2 - (sP_s)^2} \\ Q_{c\min} = -\sqrt{S_{c\max}^2 - (sP_s)^2} \end{cases} \tag{4}$$

C. Reactive Power Limitations of the DFIG Stator

Based on the orientation of the grid voltage vector, the rotor current can be expressed as [10]:

$$\begin{cases} i_{rd} = \dfrac{L_s}{L_m} i_{sd} \\ i_{rq} = \dfrac{L_s}{L_m} i_{sq} - \dfrac{u_s}{L_m w} \end{cases} \tag{5}$$

where i_{rd} and i_{rq} are the *d*- and *q*-axis components of the rotor current, i_{sd} and i_{sq} are the *d*- and *q*-axis components of the stator current, L_s is the stator inductance, L_m is the mutual inductance of stator and rotor, u_s is the stator voltage, and ω is the synchronous angular velocity.

It is well known that $i_{rd}^2 + i_{rq}^2 = i_r^2$, so there is

$$\left(\frac{L_s}{L_m} i_{sd}\right)^2 + \left(\frac{L_s}{L_m} i_{sq} - \frac{u_s}{L_m w}\right)^2 = i_r^2 \le I_{r\max}^2 \tag{6}$$

where $I_{r\max}$ is the maximum current of the rotor-side converter.

Similarly, the stator current can be written as:

$$i_{sd}^2 + i_{sq}^2 = i_s^2 \le I_{s\max}^2 \tag{7}$$

where $I_{s\max}$ is the maximum current of the stator.

The active and reactive power of DFIG stator can be presented as [10]:

$$\begin{cases} P_s = \dfrac{3}{2} u_s i_{sd} \\ Q_s = \dfrac{3}{2} u_s i_{sq} \end{cases} \tag{8}$$

Then,

$$\begin{cases} i_{sd} = \dfrac{2P_s}{3u_s} \\ i_{sq} = \dfrac{2Q_s}{3u_s} \end{cases} \quad (9)$$

Combine (9) with (6) and (7), there are

$$\begin{cases} P_s^2 + \left(Q_s + \dfrac{3u_s^2}{2wL_s}\right)^2 \le \left(\dfrac{3u_s L_m I_{r\max}}{2L_s}\right)^2 \\ P_s^2 + Q_s^2 \le \left(\dfrac{3u_s I_{s\max}}{2}\right)^2 \end{cases} \quad (10)$$

According to (10), the reactive power limitations of DFIG stator are shown in Fig. 2, where the thick solid line is the boundary values of reactive power.

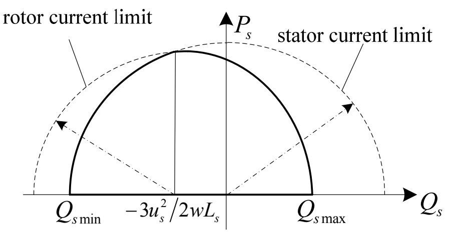


Figure 2. Reactive power limitations of DFIG stator

D. *Reactive Power Limitations of the DFIG*

In order to establish the magnetic field, the DFIG stator needs to absorb reactive power from the grid, which leads to the asymmetric reactive power limitations in Fig. 2. That is to say, the maximum capacitive reactive power of DFIG stator is less than the maximum inductive reactive power. Assuming the DFIG is equipped with a bank of capacitors with the capacitance $C = 3/2wL_s$ and considering them as a whole, the reactive power limitations of DFIG will be shifted to the right direction and a symmetrical one can be obtained as:

$$\begin{cases} Q_{g\max} = \sqrt{(\dfrac{3u_s L_m I_{r\max}}{2L_s})^2 - P_s^2} + \sqrt{S_{c\max}^2 - (sP_s)^2} \\ Q_{g\min} = -\sqrt{(\dfrac{3u_s L_m I_{r\max}}{2L_s})^2 - P_s^2} - \sqrt{S_{c\max}^2 - (sP_s)^2} \end{cases} \quad (11)$$

III. Reactive Power Control Strategy of DFIG Wind Farms

Since a DFIG wind turbine has the capability of absorbing and generating reactive power, a DFIG wind farm thus can not only generate active power, but also generate or absorb the reactive power to stabilize the grid voltage. The reactive power is mainly controlled in two modes, i.e. power factor control and voltage control. Both the two modes take the point of common coupling (PCC) as the reference point. The voltage or power factor at PCC is detected and is compared with the reference to calculate the reactive power demanded by the grid. Based on the demanded reactive power and the reactive power limitations of each DFIG wind turbine, the number of DFIGs that take part in the reactive power support is determined. The control mode of these DFIGs is consequently changed from unity power factor control to voltage control.

The overall reactive power control strategy is shown in Fig. 3, where U_N is the rated voltage, U_{pcc} is the measured voltage, i.e., the voltage at PCC, $\Delta U\%$ is the voltage deviation, Q_{ref} is the demanded reactive power by the grid, and Q_{ref}^i is the reactive power allocated to unit *i*.

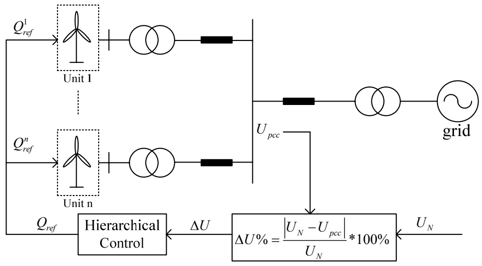


Figure 3. Reactive power control strategy

The control process is illustrated in detail as follows:

1) Monitor the real-time active power of each DFIG wind turbine, and calculate the reactive power limitations of each turbine according to (11). The reactive power limitation of the wind farm is calculated by $Q_{wf\max} = \sum_{i=1}^{n} Q_{ig\max}$.

2) Detect the voltage at PCC U_{pcc} and compare it with the rated voltage U_N . The reactive power demanded by the grid Q_{ref} is obtained based on the voltage deviation $\Delta U\%$. According to the reactive power limitations of each wind turbine, choose the minimum number of units and allocate the demanded reactive power Q_{ref} to these units evenly. If $Q_{wf\max} < Q_{ref}$, then all the units will take part in the voltage regulation, and the pitch angle of each wind turbine should be adjusted to decrease the active power and enlarge the reactive power limitations until $Q'_{wfmax} \geq Q_{ref}$ is satisfied.

3) The reactive power allocated to unit *i* Q_{ref}^i is allocated again between each unit's stator and grid-side converter, and the stator has a priority. That means if Q_{ref}^i is in the thick-solid-line region shown in Fig. 2, the stator will support Q_{ref}^i alone, if not, Q_{ref}^i will be generated by the stator together with the grid-side converter.

4) The control modes of the involved units are switched to generate the reactive power and maintain the voltage. When finished, return to step 1).

IV. Case Study

An example case is implemented on the PSCAD/EMTDC platform, as shown in Fig. 4. A 100MW wind farm is connected to a 220 kV power grid through overhead lines after two-stage boosts. The wind farm is simplified to have only three wind turbines G1, G2 and G3, their capacities are 30 MW, 30 MW and 40 MW, respectively. Capacities of the rotor-side and grid-side converters are both 30% of each unit's total capacity. Two loads, Load1 and Load2, are connected to the 10 kV and 6 kV buses.

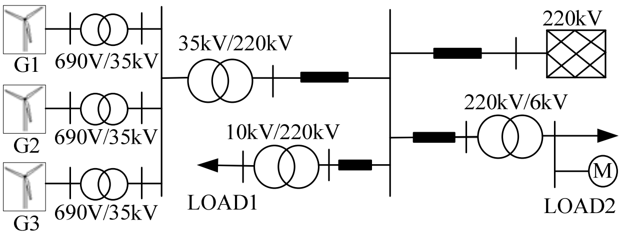
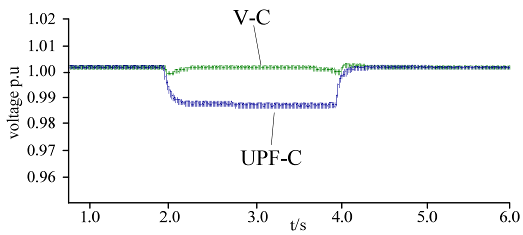


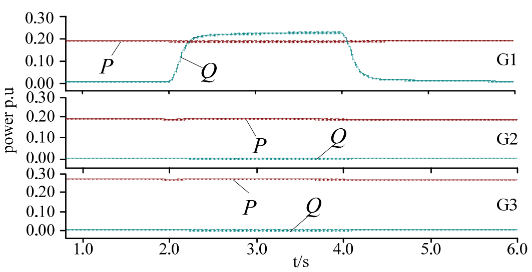
Figure 4. An example system for simulation

To verify the reactive power control strategy proposed, two cases that demonstrate small and big reactive power disturbances are simulated.

Case1: Assuming that the wind speed is always 10 m/s, and the 80 MVA Load1 at the 10 kV bus increases by 50% from 2 s to 4 s. The simulation results are shown in Fig. 5. It can be seen that if the wind farm works at the unity power factor of 1, the voltage at PCC drops to 0.984 p.u. when Load1 changes. If the proposed control strategy is applied, G1 will be picked on and then switched to the voltage control mode. Reactive power of 0.24 p.u. is injected to the power grid by G1, therefore, the voltage at PCC hardly changes during the load disturbance. The other two units G2 and G3 always work at the unity power factor of 1 from beginning to end.



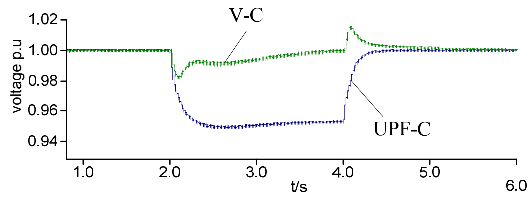
(a) Grid voltage



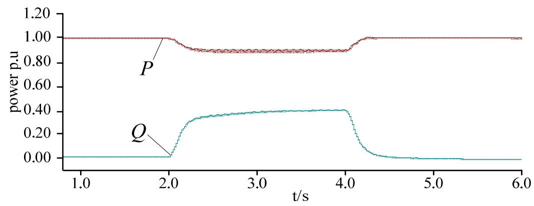
(b) Output power of wind turbines

Figure 5. Reactive power control during small load disturbance

Case 2: Assuming that the wind speed is always 13 m/s, and a 50 Mvar reactive load is connected to the 6 kV bus from 2 s to 4 s. In this case, the wind farm works at the full power and can hardly generate any reactive power due to the rated power limitation. The simulation results are shown in Fig. 6. It can be seen that if the wind farm works at the unity power factor of 1, the voltage at PCC drops severely to 0.955 p.u. when Load2 changes. If the proposed control strategy is applied, the three units G1, G2 and G3 are all picked on since the demanded reactive power is bigger than the reactive power limitation of the wind farm. The pitch angles of the three units are all adjusted from 0° to 3.5°, sacrificing a certain active power of the wind farm, that is from 1 p.u. to 0.914 p.u., and enlarging the reactive power limitation of the wind farm. During the voltage drop, the wind farm provides 0.4 p.u. reactive power to the grid, helping the voltage return to normal.



(a) Grid voltage



(b) Output reactive power of the wind farm

Figure 6. Reactive power control during a large load disturbance

In Case 2, the wind farm works at the full power. Once a large load disturbance occurs, dynamic reactive power compensation devices such as SVG should have been installed to provide reactive power in real time. However, in Case 2, thanks to the reactive power control strategy proposed, the wind farm just sacrifices a certain active power to provide reactive power, no dynamic reactive power compensation device is required, which is more economical.

V. Conclusions

This paper analyzes the reactive power limitations of a DFIG wind turbine quantitatively and proposes a more flexible reactive power control strategy of a grid-connected DFIG wind farm. Simulation results show that the control strategy proposed can wonderfully suppress the voltage fluctuations at PCC caused by load changes. This control strategy intends to pick on as few DFIG wind turbines as possible to take part in the voltage regulation and generate the demanded reactive power by the grid. If the maximum reactive power generated by the wind farm still cannot satisfy the grid's demand, then the wind farm will sacrifice a certain active power to generate more reactive power. The strategy can be applied when load disturbances occur. Short-circuit faults are not taken into account since fault ride-through control does not belong to the research scope of this paper. The strategy make wind farms involved in the voltage regulation, thus provides more choices for the grid in real-time scheduling. Dynamic grouping of units and optimal allocation of reactive power among units need further study.

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