A Novel Aggregation Method for Doubly Fed Wind Farm

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Abstract. With the increasing penetration of wind power, many problems like frequency and voltage stability appear frequently, so the power grid gradually requires that the wind farm can be dispatched and controlled. In this paper, a new aggregation method is proposed to calculate the aggregated active and reactive power regulation range of a doubly-fed wind farm, which provides a dispatching reference for the power system control center. In this method, voltage security and different operation states of wind turbines and internal power losses of the wind farm are considered. Finally, the actual aggregated P-Q regulation range of the wind farm that can ensure operation safety is obtained. A wind farm with 25 doubly fed induction generator (DFIG) wind turbines is used to verify the proposed aggregation method.

1. Introduction

With the increasing installed capacity of wind power generation, the connection between wind farm and the power grid becomes more and more compact. The external characteristics of the wind farm will have an important impact on the safety and control strategy of the power grid. The uncertainty of wind power causes a series of problems, such as voltage fluctuation, frequency stability, power flow inversion. Therefore, wind farms should have certain self-regulation and support capabilities, and cannot rely on the support of the power grid. Therefore, wind farms should have the ability to adjust their active and reactive power, and to respond the dispatching of power system control center.

At present, the common wind farm aggregation modelling methods can be divided into full aggregation and semi aggregated techniques. In [1] the semi aggregated method is adopted, which consists of all wind turbines and one equivalent generator. While in [2] the full aggregated method is adopted, which consists of one equivalent wind turbine and one equivalent generator, and an equivalent wind speed of all wind turbines is calculated. A rotor side converters aggregated method is proposed in [3], which focuses on the problem that operating states of wind turbines in wind farm is totally different. All the above studies aggregate the wind farm to one equivalent generator, so their aggregated method is too ideal in some cases. For the power grid, the power system control center is concerned about the external characteristics of the wind farm, rather than the specific characteristics of all wind turbines. If we get the aggregated active and reactive power regulation range of the wind farm, we will meet the dispatching requirements of power system control center.

DFIG has a strong ability to adjust reactive power [4,5], and many studies pay attention to this reactive power adjustment ability [6,7]. To calculate the aggregated P-Q regulation range, many previous studies ignore the topology and voltage constraints of the wind farm, and algebraically add
the reactive power regulation range of each wind turbine, as shown in [8]. This kind of method is unreasonable for large wind farms.

Aiming at above problems, this paper proposes a novel method to calculate the aggregated P-Q regulation range of a doubly fed wind farm, which provides a reference for power system control center. Section 2 contains the overall description of the active and reactive control range of DFIG. Section 3 sets up the mathematical model that calculates the aggregated P-Q regulation range. In section 4, the model is simplified, and the specific solution flow to calculate the aggregated P-Q regulation range of a wind farm is given. Case studies are presented and discussed in section 5.

2. P-Q regulation range of DFIG

The P-Q regulation range of DFIG can be deduced from the steady-state model of DFIG. The reactive power regulation capability of DFIG is composed of two parts, stator reactive power and grid side converter reactive power. The reactive power regulation capability of stator side is limited by the maximum current of stator and rotor, while the reactive power regulation capability of grid side converter is limited by its capacity. The reactive power regulation range of DFIG (i.e., P-Q regulation range), can be presented as \( Q_{\text{max},Wi} \) and \( Q_{\text{min},Wi} \), as shown in (1) and (2).

\[
Q_{\text{max},Wi} = -1.5 \frac{U_s^2}{X_s} + \sqrt{\left(1.5 \frac{X_s U_s}{I_{\text{max},s}} \right)^2 - \left( \frac{P_{\text{min},Wi}}{\omega_{r,\text{max}}} \right)^2} + \sqrt{S_{\text{max}}^2 - \left[ \left(1 - \frac{P_{\text{min},Wi}}{\omega_{r,\text{max}}} \right) \frac{P_{\text{min},Wi}}{\omega_{r,\text{max}}} \right]^2}
\]

\[
Q_{\text{min},Wi} = -\sqrt{\left(1.5 \frac{U_s I_{\text{max},s}}{I_{\text{max},r}} \right)^2 - \left( \frac{P_{\text{max},Wi}}{\omega_{r,\text{max}}} \right)^2} - \sqrt{S_{\text{max}}^2 - \left[ \left(1 - \frac{P_{\text{max},Wi}}{\omega_{r,\text{max}}} \right) \frac{P_{\text{max},Wi}}{\omega_{r,\text{max}}} \right]^2}
\]

where \( U_s \) denotes stator single-phase voltage, \( I_{\text{max},s} \) and \( I_{\text{max},r} \) are stator and rotor maximum single-phase current, \( \omega_{r,\text{max}} \) is the rotor speed of DFIG \( Wi \). \( S_{\text{max}} \) is maximum capacity of grid side converter. \( X_s \) and \( X_m \) are stator reactance and excitation reactance of DFIG.

In addition to equations (1) and (2), the P-Q regulation range of DFIG should also be limited by the maximum active power \( P_{W,\text{max}} \).

Given \( \omega_{r,\text{max}} \) and \( U_s \), the P-Q regulation range of DFIG is shown in the gray area in Figure 1. \(-1.5 \frac{U_s^2}{X_s}\) represents inductive reactive power absorbed by DFIG. Stator and rotor current limitation, reactive power regulation capability of grid side converter, and the limitation of \( P_{W,\text{max}} \), constitute the P-Q regulation range of DFIG.

![Figure 1. The P-Q regulation range of DFIG](image)

Equations (1) and (2) show that the P-Q regulation range of DFIG is not only depended on P and Q, but also influenced by \( \omega_{r,\text{max}} \) and \( U_s \). The P-Q regulation range is approximate to an ellipse, so \( \omega_{r,\text{max}} \) will
impact semimajor axis of this ellipse. When $\omega_{r,W_i}$ is increased or decreased, the ellipse will be elongated or shortened. $U_i$ will impact the dot and radius of this ellipse. Therefore, when calculating the aggregated P-Q regulation range of the wind farm, it is necessary to take into account the state of the rotor speed and terminal voltage of each DFIG.

3. Mathematical modelling

To obtain the aggregated P-Q regulation characteristic of the wind farm, it is necessary to consider the topology, voltage limitation and power flow loss of the wind farm. If all wind turbines of the wind farm output their maximum reactive power, voltages of some wind turbines may exceed the normal level, and may lead to generators outage. In this section, the mathematical model to calculate the aggregated P-Q regulation range is established. The objective is to maximize and minimize the reactive power output of the wind farm. The objective function is expressed as follows:

$$\max F_1 = Q_{\text{PCC}}$$
$$\min F_2 = Q_{\text{PCC}}$$

where $Q_{\text{PCC}}$ is the reactive power output at point of common coupling (PCC) of the wind farm.

Constraints are as follows:

(1) Power flow equations:

$$U_i^2 = U_i^2 - 2(r_i P_{ij} + x_i Q_{ij}) + (r_i^2 + x_i^2)I_{ij}^2$$
$$P_{ij} = \sum_{j=1}^{n} P_{jk} + r_i I_{ij}^2 - P_{Wj}, \quad j \in N$$
$$Q_{ij} = \sum_{j=1}^{n} Q_{jk} + x_i I_{ij}^2 - Q_{Wj}, \quad j \in N$$

$$I_{ij}^2 = \frac{P_{ij}^2 + Q_{ij}^2}{U_i^2}$$

where $N$ is the set of wind farm nodes. $P_{ij}$ and $Q_{ij}$ are the line active and reactive power from bus $i$. $P_{Wj}$ is the active power of DFIG at bus $j$. $Q_{Wj}$ is the reactive power of DFIG at bus $j$. $U_j$ is the voltage of bus $j$. $r_i$ and $x_i$ are the resistance and reactance of line $ij$.

(2) Node voltage magnitude limits:

$$U_j \leq U_i \leq \bar{U}_j, \quad i \in N$$

where $U_j$ and $\bar{U}_j$ are the minimum and maximum voltage limits of bus $i$.

(3) The P-Q regulation range of each DFIG:

$$0 \leq P_{Wj} \leq P_{\text{W,max},i}, \quad i \in N_W$$

$$Q_{\text{min},Wj} \leq Q_{Wj} \leq Q_{\text{max},Wj}, \quad i \in N_W$$

where $P_{\text{W,max},i}$ is the maximum wind power of DFIG at bus $i$, and it can be get through wind power prediction. $N_W$ is the set of DFIG wind turbines.

(4) Total active power output limit of the wind farm:

$$P_{\text{PCC}} = P_{\text{set}}$$

where, $P_{\text{set}} = 0, \ldots, P_{\text{PCC,max}}$ is the total active power output limit which is set point-by-point in advance. Every $P_{\text{set}}$ corresponds with a maximum and a minimum reactive power output.

This model fully considers the voltage safety of the wind farm internal nodes, as well as the different operating states of wind turbines. Through ultra-short-term wind power prediction, the maximum active power of each wind turbine at one point in the future can be obtained, and then the aggregated P-Q regulation range characteristic of the wind farm can be calculated. It should be noted that the total active power output of the wind farm is given point by point, and this optimization model just calculate one point of the aggregated P-Q regulation range curve. Therefore, the aggregated P-Q regulation range of double-fed wind farm at a certain moment can be obtained by calculating multiple points.
4. Model simplification and solution

4.1. Model simplification

The mathematical model in section 3 is nonlinear and difficult to solve, and in this section, simplifications are proposed to make the model solved conveniently and quickly. The simplifications include the linearization of power flow equations and the P-Q regulation range of each DFIG. After these simplifications, a linearized model is obtained.

Noting the power flow constraint represented by equations (5) - (8), the nonlinear term is \(I_i^2\), so if we linearize \(I_i^2\), the linearized power flow equations will be obtained. The Taylor expansion of the power flow equations is carried out around the operating point \((P_{\alpha 0}, Q_{\alpha 0}, U_{\alpha 0})\) with the second-order and higher-order terms ignored

\[
I_i^2 = \frac{1}{U_{\alpha 0}^2} \left( 2P_{\alpha 0}P_i + 2Q_{\alpha 0}Q_i - \frac{P_{\alpha 0}^2 + Q_{\alpha 0}^2}{U_{\alpha 0}^2} U_i^2 \right) \tag{13}
\]

It is noted that the power flow constraint only contains the square term of voltage, so we use \(V_i\) to replace \(U_i^2\). And then, the power flow equations are linearized.

When the rotor speed and terminal voltage are given, the P-Q regulation range of DFIG is approximate to an ellipse, which can be piecewise linearized. To consider the impact of the terminal voltage and rotor speed, measurement values of the last time are used to replace the rotor speed and terminal voltage in equation (11), and then the piecewise linearization of the P-Q regulation range is carried out. By selecting appropriate points, it can be divided into 5 line segments, as shown in Figure 2. Results show that the linearization carried out by 5 segments has high precision.

![Figure 2. The piecewise linearization of the P-Q regulation range of DFIG](image)

4.2. Solving process

When solving the optimization model, \(P_{set}\) is set several times, which leads to cycle calculation of the model. By setting suitable number of \(P_{set}\) and the simplification in section 4.1, the speed of calculation can be increased. The solving process is summarized as Figure 3.
5. Case study

In this section, a wind farm, including 25*1.5 MW doubly fed wind turbine generators, was used for the case study. Its topology structure is shown in Figure 4. Each DFIG is connected to 35kV lines through 690V/35kV transformer (not shown in Figure 4). Parameters of DFIG used in this paper are given in Table 1. Voltage limits are set to be within the range 0.95-1.05 p.u. In this case study, the voltage of high voltage network is set to be 1.0 p.u.

In this section, the historical wind power data is used, and each DFIG of the wind farm have different wind speed. The maximum wind power of each DFIG is given in Figure 5. At this moment, the average wind speed of the wind farm is high, and the maximum active power of each DFIG is different. To contrast the calculation result, method A is used to calculate the aggregated P-Q regulation range of the wind farm, which is algebraic addition of all wind turbines. The P-Q regulation range result of method A is shown in Figure 6. Using method of this paper, the aggregated P-Q regulation range of the doubly fed wind farm at this point is calculated, and is also shown in Figure 6.

Figure 3. The solving process of the aggregated P-Q regulation range

Figure 4. Topology of the wind farm
Table 1. Parameters of DFIG

| Parameter          | Value     | Parameter          | Value     |
|--------------------|-----------|--------------------|-----------|
| Rated voltage      | 690 V     | Excitation reactance | 1.720 Ω   |
| Rated capacity     | 1.5 MW    | $I_{max}$          | 1565.8 A  |
| Stator reactance   | 1.773 Ω  | $I_{max}$          | 1649.5 A  |

Figure 5. The maximum wind power of each DFIG

From Figure 5, it can be observed that the aggregated P-Q regulation range of the wind farm calculated by this paper’s method, is obviously smaller than the range calculated by method A. Furthermore, the variation characteristic of the ability to absorb reactive power is different. The aggregated P-Q regulation range obtained by method A is similar to a single DFIG’s P-Q regulation range, and this method doesn’t consider voltage limits of wind farm internal nodes. The method of this paper fully considers the voltage level of every DFIG and nodes inside the wind farm. Figure 6 shows that using this paper’s method, when $P_{PCC}$ is small, the lagging reactive power output ability of the wind farm is weaken. The reason is that when all wind turbines output the lagging reactive power, the voltage will be raised, and to ensure voltage security, the lagging reactive power output should be limited. But as $P_{PCC}$ increasing, the P-Q regulation range of each DFIG will be the main limit to $Q_{PCC}$. Using this paper’s method, the capacitive reactive power output ability of the wind farm increases first and then decreases with the increasing of $P_{PCC}$. If wind turbines output the capacitive reactive power, the voltage will be reduced. As $P_{PCC}$ increasing, the voltage is rised, and the capacitive reactive power output ability is heightened. But when $P_{PCC}$ is closed to rated capacity, capacitive $Q_{PCC}$ will decrease because of the P-Q regulation range limit of each DFIG.

Results show that the actual aggregated P-Q regulation range of the wind farm is obviously smaller when considering the voltage security and topology inside the wind farm. This aggregated P-Q characteristic has more practical reference significance for power system control center.
6. Conclusion
In this paper, a novel method to calculate the aggregated P-Q regulation range of doubly fed wind farm is proposed. It is important that voltage security inside the wind farm and different operation states of wind turbines should be considered. If all wind turbines output their maximum reactive power, low voltage or overvoltage will appear inside the wind farm, which is very unsafe to generators. This method will provide a credible dispatching range of the wind farm for power system control center.

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References
[1] L. M. Fernández, J. F, J. R. Saenz. Aggregated dynamic model for wind farms with doubly fed induction generator wind turbines. Renewable Energy, 33(1), 129 (2008).
[2] A. J. Xia, Z. X. Lu, Y. Min, et al. An aggregated model of wind farm composed of doubly fed induction generators. Power System Technology, 39(7), 1879 (2015).
[3] Y. Q. Jin, P. Ju, X. P. Pan. Analysis on controller aggregation method for equivalent modelling of DFIG-based wind farm. Automation of Electric Power Systems, 38(3), 19 (2014).
[4] Q. Liu, Z. M. Wang. Reactive power generation mechanism & characteristic of doubly fed variable speed constant frequency wind power generator. Proceedings of the CSEE, 31(3), 82 (2011).
[5] H. Zhang, Y. C. Zhang, D. W. Yang. Two-vectors-based model predictive direct power control of doubly fed induction generator for grid connection and power regulation. Transactions of China Electrotechnical Society, 31(5), 69 (2016).
[6] A. H, A. M. Coordinated reactive power management in power networks with wind turbines and FACTS devices. Energy Conversion & Management, 52(7), 2575 (2011).
[7] H. Y. Liu, P. Guan. Optimal control of doubly fed induction generator systems. Electrical Engineering, 17(3), 13 (2016).
[8] J. Cao, R. L. Zhang, G. Q. Lin, et al. A voltage control strategy for wind farms using doubly fed induction generator wind turbines. Automation of Electric power Systems, 33(4), 87 (2009).