Small-Signal Stability Effects of Wind Power Integration Capacity and Accommodation on Interconnected Power Systems

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Abstract. Wind generation is considered as an economical and environmental friendly way of electricity production. The large-scale wind generation may impact the power systems in almost every aspect. This paper presents the small-signal stability effects of wind power integration capacity and accommodation on interconnected power systems. Furthermore, a study case based on the comprehensive model of the doubly fed induction generator (DFIG) has been conducted and analyzed by using the eigenvalue analysis and dynamic time-domain simulation. The IEEE 3 generators and 9 nodes system has been used in the analysis. Results show that the integration of DFIG wind turbines in a system may improve the damping of interconnected power system, and the interregional low frequency oscillation can be weaken. This study can provide effective basis for the plan and operation of wind power integration into an interconnected power system.

Introduction

With the deterioration of the ecological environment and the gradual depletion of fossil fuels, renewable energy has become a hot spot in the recent scientific research [1]. Wind energy has the characteristics of renewable, zero pollution, abundant reserves, which is considered as an economical and environmental friendly way of electricity production [2, 3]. Compared with thermal power and hydropower, wind power tends to be variable and uncertain since the wind depends on natural conditions, which introduces lots of new challenges for power system low frequency regulation and control [4, 5].

In recent years, many research efforts have been devoted to the development of stability of power system with wind power integration [6-19]. The impact of the damping characteristic of power grid with wind turbines interconnected was firstly proposed by JG. Slootweg in [6] in the year 2003. The impact of wind power integration on low frequency oscillation and small-signal stability of power system by using eigenvalue analysis method was carried out in [7-12]. Considering the difference of integration capacity, the impact of doubly fed wind generator integration on low frequency oscillation of power system was analyzed in [13] by using WSCC 3 generators and 9 nodes system. Taking the practical model of the Nordic power grid as an example, the influence of different types of wind turbines on the interconnected system was analyzed in [14]. Large capacity of single machine was considered as the main trend of wind power development in the future in [15, 16], the effect of different wind conditions and system capacity of wind power on the stability of the system was analyzed. Wind power base integration in Denmark grid is taken as examples in [17], in which the effect on power system and control countermeasures is discussed with wind power integration.

There are two general ways of accommodation with wind power integration in the actual operation of wind power system: a) Accommodated locally as a kind of distributed power integrating to the distribution network when the capacity of wind power is smaller; b) Accommodated distantly by high voltage power transmission when the capacity is bigger.
A number of research efforts have been devoted to the impact of wind power integration on power system security and stability recently. However, few researches on the impact on interconnected power system considering both capacity of wind power integration and accommodation were proposed according to the current literatures. In this paper, the model of DFIG is built based on studies in [6-16], small-signal stability effects of wind power integration capacity and accommodation on interconnected power systems is studied as well, which can provide reference for comprehensive analysis of the plan and operation of wind power integration into an interconnected power system.

**Wind Power Model**

The most widely used wind turbine model based on doubly fed induction generator (DFIG) is shown in Fig. 1. The stator of DFIG is connected to the power system directly, and the rotor is connected to system with pulse width modulation (PWM) converter, with which the decoupling control of active and reactive power can be achieved.

In Fig.1, \( v \) is wind speed, \( T_m \) and \( T_e \) are mechanical torque of wind turbine and electromagnetic torque of generator rotor respectively; \( \omega_t \) and \( \omega_g \) are speed of wind turbine and generator; \( \theta_g \) is generator rotor angle; \( \beta \) is pitch angle, \( \beta_{ref} \) is reference of pitch angle; \( P \) and \( Q \) are active and reactive power, in which subscript \( s \) is stator power and \( r \) is rotor power; \( P_c \) and \( Q_c \) are absorbed from power system by grid-side converter respectively; \( P_g \) and \( Q_g \) are active and reactive power flowed into power system from wind power system with DFIG.

![Fig. 1. The dynamic model configuration of wind turbine generator.](image)

**Shaft Model**

Two-mass Shaft Model is generally used in transmission device [7], the shaft model can be expressed as

\[
\begin{align*}
\frac{d\omega_t}{dt} &= \frac{1}{2H_t} (T_m - T_e - D_t \omega_b) \\
\frac{d\theta_t}{dt} &= \omega_b (\omega_t - \phi_t) \\
\frac{d\omega_b}{dt} &= \frac{1}{2H_g} (T_m - T_{sh})
\end{align*}
\] (1)

Where, \( H_t \) and \( H_g \) are the inertia time constant of wind turbine and generator respectively; \( \theta_t \) and \( \omega_b \) are shaft twist angle and system synchronous speed respectively; \( D_t \) is the damping coefficient of wind turbine; \( T_{sh} \) is the shaft torque of wind turbine.
DFIG Model

A per-unit fourth DFIG model of wound-rotor induction motor in $d$-$q$ coordinate system in [18] is adopted in this paper.

\[
\begin{align*}
\frac{X_s' \, di_s}{\omega_s \, dt} &= -(r_s + x_s \, \frac{s}{\omega_s^2})i_s + X_s' \, i_q + v_s \\
&\quad - (1 - s) e_{s'} \, \frac{1}{\omega_s^2} e_{s'} - \frac{L_s}{L_s} v_{s'} \\
\frac{X_q' \, di_q}{\omega_q \, dt} &= -(r_s + x_s \, \frac{s}{\omega_s^2})i_q - x_s' i_s + v_s \\
&\quad - (1 - s) e_{s'} \, \frac{1}{\omega_s^2} e_{s'} - \frac{L_s}{L_s} v_{s'} \\
\frac{de_{s'}}{dt} &= s \, \omega \, e_{s'} - \omega \, \frac{L_s}{L_s} v_{s'} - \frac{1}{T_o} \left[ e_{s'} \, (x_s - x_s') i_{s'} \right] \\
\frac{de_{s'}}{dt} &= -s \, \omega \, e_{s'} + \omega \, \frac{L_s}{L_s} v_{s'} - \frac{1}{T_o} \left[ e_{s'} \, (x_s - x_s') i_{s'} \right]
\end{align*}
\]

Where, $L_s$ and $L_r$ are self-inductance of stator and rotor respectively; $r_s, r_r, x_s$ and $x_s'$ are stator resistance, rotor resistance, stator reactance and stator transient reactance respectively; $e'_{ds}$ and $e'_{qs}$ are component of transient electric potential in $d$-$q$ coordinate respectively; $T_o'$ is rotor time constant; $i_{ds}$ and $i_{qs}$ are component of stator current in $d$-$q$ coordinate respectively; $v_{ds}, v_{qs}$ and $v_{dr}, v_{qr}$ are voltage of stator and rotor in $d$-$q$ coordinate respectively.

Pitch Model

Pitch control model is adopted as shown in (3) generally in order to make the wind turbine output stable and increase the conversion rate of wind energy, its strategy is shown in Fig. 2.

\[
\frac{d\beta}{dt} = \frac{1}{T_\beta} (\beta_{ref} - \beta)
\]

![Fig. 2. Control diagram of pitch control strategy.](image)

Converter Model

Excitation voltage of DFIG is provided by the machine side converter, and the voltage of grid side converter capacity is controlled and maintained by DC control system; DC side of two converters are provided by one capacitor for voltage support. Its power equation can be expressed as

\[
\begin{align*}
P_r &= P_s + P_{dc} \\
P_r &= v_s i_s + v_q i_q \\
P_s &= v_s i_s + v_q i_q \\
P_{dc} &= v_{dc} i_{dc} = -Cv_{dc} \frac{dv_{dc}}{dt}
\end{align*}
\]
Where, $P_{DC}$ is active power of DC tie line; $i_{dr}$ and $i_{qr}$ are component of stator current in $d$-$q$ coordinate respectively; $i_{dg}$, $i_{qg}$ and $v_{dg}$, $v_{qg}$ are current and voltage of grid side converter in $d$-$q$ coordinate respectively; $i_{DC}$ and $v_{DC}$ are current and voltage of capacitor DC respectively; $C$ is capacity of capacitor.

Equation (5) can be obtained based on (4)

$$C_{v_{DC}} \frac{dv_{DC}}{dt} = v_{dg} i_{dr} + v_{qg} i_{qr} - (v_{dr} i_{dr} + v_{qr} i_{qr})$$

(5)

**Small Signal Stability Analysis**

Small signal stability characterizes the ability of power systems to maintain synchronous operation after small interfering. For small signal stability of power system with wind turbine or wind power connected, small signal stability analysis is based on theory of linear system and Lyapunov first law, which linearize the differential-algebraic equations describing the dynamic characteristics of the power system at the stable operating point, model of power system after linearized can be expressed as

$$\Delta x = A \Delta x$$

(6)

Where, $\Delta x$ is state variable increment of dynamic characteristic of system, $A$ is the state matrix of linearized system. Then the small signal stability of power system can be judged based on the eigenvalues and eigenvectors of $A$.

For the complex eigenvalue $\lambda = \sigma + j \omega$, the corresponding oscillation frequency is $f = \omega / 2 \pi$, the corresponding damping ratio is defined as

$$\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}}$$

(7)

Participation factor is to describe the relationship between state variables and modes, the calculating formula of the participation factor from state variable $i$ to eigenvalue is

$$p_i = \frac{w_i v_i}{\sqrt{w_i^T w_i} \sqrt{v_i^T v_i}}$$

(8)

For any eigenvalue, vector $w_i$ with $n$ columns is called right eigenvector of $\lambda_i$ when it satisfies $A w_i = \lambda_i w_i$ ($i = 1, 2, \ldots, n$); vector $v_i$ with $n$ rows is called left eigenvector of $\lambda_i$ when it satisfies $v_i A = v_i \lambda_i$ ($i = 1, 2, \ldots, n$).

**Case Study**

**Description of the Test System**

The 3 generators 9 nodes system is shown in Fig. 3. Specific parameters can be seen in [20]. In the practical wind power integration system, wind farms generally contain a number of turbines, in this paper, the model of single turbine is used to simulate the whole wind farm in order to simplify the analysis.
Influence of Wind Power Integration Capacity on System

The active power of the 2 PV nodes of the initial system is 151MW and 85MW respectively, the output of the wind turbine generator is increased to 4MW, 8MW and 13MW gradually, in order to ensure the transmission power of the tie line, output of corresponding synchronous generators on bus 2 is adjusted.

Tab. 2 shows eigenvalues of the system with different wind turbine output, where permeability is the percentage of the wind turbine in the total load, correlative units are got from the correlation factor calculated by (8). Distribution of eigenvalues with 4MW wind turbine output is shown in Fig. 4.

It is can be seen that there oscillation mode; A new oscillation mode 4 and is added to the system with wind power integration. In the original oscillation mode, damping ratio of mode 1 and 3 are increased, and the damping ratio increases with the increase of the integration capacity; damping ratio of mode 2 picks up after a drop.

Response curves of systems with different grid connected capacity are shown in Fig. 5-6 when a short circuit occurred at 1s.

Fig. 5 shows the voltage curves of bus 2 and 11, it is can be seen that: voltage of bus 11 kept stable at first and dumped when the fault occurred without wind turbine integration; The voltage rebounded after a slight decline before fault occurred with wind turbine integration. With the fault cleared, the voltage rose over rated voltage then down to stable operation, it was found that the voltage of bus 2 had declined with wind turbine integration. The curve of voltage of bus 11 shows that the wind turbine voltage dropped at the moment of failure, and recovered to stable operation with a slight fall when the fault was cleared.
Response curve of G2 with different wind turbine output is shown in Fig. 6.

The power angle of G1 is taken as the reference value in the power angle response curve in Fig. 6. It is can be seen from the curve that the power angle fluctuation of G2 increased with the increasing of wind power integration capacity.

![Fig. 5. Response of bus voltage with different wind turbine output.](image1)

![Fig. 6. Response curve of G2 with different wind turbine output.](image2)

**Influence of Different Accommodation of Wind Power on System**

Change the location of wind turbine from bus 2 to bus 8, the output of wind power is 4MW. Now, the wind turbine is connected to the bus with load directly, which is the local accommodation mode. Eigenvalues in Tab. 2 and response curve in Fig. 7 can be obtained under the same conditions with 3.2.

According to the contrast between Tab. 1 and Tab. 2, damping ratio of mode 1, 2, 3 decreased. It can be drawn that it is unbeneifical to reduce the low frequency oscillation when wind turbine is in the local accommodation mode. According to the study in [21], the inter-area modes are more prone to instability when areas with high wind penetrations export power to remote areas, which is consistent with the analysis in this paper.
Fig. 7. Response curve of system in local accommodation mode.

Table 1. Eigenvalues of system with wind turbine integrated at bus 4.

| wind power output(MW) | mode | eigenvalues      | frequency (Hz) | damping ratio | related unit |
|-----------------------|------|------------------|----------------|---------------|--------------|
|                       | 4    |                  |                |               |              |
| 1                     | -1.0572±12.788 | 2.0422          | 0.0824         | G₂ , G₃      |
| 2                     | -0.2101±8.3268 | 1.3257          | 0.0252         | G₁ , G₂      |
| 3                     | -0.4943±0.9946 | 0.17677         | 0.4451         | G₁ , G₃      |
| 4                     | -0.3042±0.8149 | 0.13843         | 0.3497         | G₁ , DFIG    |

With the comparison of the curves between Fig. 7 and Fig. 5-6, it is can be seen that the response of bus voltage in local accommodation mode was similar to distant accommodation mode. The power angle oscillation amplitude of G₂ paralleled with wind turbine decreased, but the oscillation time increased. It can be seen from the power curve that power of G₂ picked up after a drop when fault was removed, and maintain stable operation through oscillation finally.
Table 2. Eigenvalues of system with different wind turbine output.

| wind power output (MW) | Permeability (%) | mode | eigenvalues       | frequency (Hz) | damping ratio | related unit |
|------------------------|------------------|------|------------------|----------------|--------------|--------------|
|                        |                  | 1    | 1.0683±12.770    | 2.0396         | 0.0834       | G₂, G₃       |
|                        |                  | 2    | -0.2639±8.3808   | 1.3345         | 0.0315       | G₁, G₂       |
|                        |                  | 3    | 0.1244±0.3662    | 0.0616         | 0.3216       | G₁, G₃       |
|                        |                  | 1    | 1.079±12.7594    | 2.038          | 0.0843       | G₂, G₃       |
|                        |                  | 2    | -0.2545±8.3934   | 1.3365         | 0.0303       | G₁, G₂       |
|                        |                  | 3    | 0.5026±1.0322    | 0.1827         | 0.4378       | G₁, G₃       |
|                        |                  | 4    | 0.2925±0.7463    | 0.1276         | 0.3649       | G₁, DFIG     |
|                        |                  | 1    | 1.0817±12.756    | 2.0374         | 0.0845       | G₂, G₃       |
|                        |                  | 2    | -0.2908±8.3935   | 1.3359         | 0.0346       | G₁, G₂       |
|                        |                  | 3    | 0.5023±1.0309    | 0.1825         | 0.4380       | G₁, G₃       |
|                        |                  | 4    | 0.2871±0.7743    | 0.1314         | 0.3477       | G₁, DFIG     |
|                        |                  | 1    | 1.068±12.7622    | 2.0383         | 0.0834       | G₂, G₃       |
|                        |                  | 2    | -0.2249±8.326    | 1.3256         | 0.0390       | G₁, G₂       |
|                        |                  | 3    | 0.4877±0.9969    | 0.1766         | 0.4394       | G₁, G₃       |
|                        |                  | 4    | 0.3003±0.8029    | 0.1364         | 0.3503       | G₁, DFIG     |

Conclusion

Based on the model of the doubly fed induction generator, detailed analysis and comparisons of wind power integration capacity and accommodation was carried out on a three machines nine nodes system, the following conclusions are obtained:

a) Regulating the output power of the wind turbine, and adjusting the output power of the synchronous generator to keep the system tie line transmission power constant, the damping ratio of the system showed a rising trend with the increase of wind power capacity. b) Changing the position of wind power integration, the damping ratio of local accommodation mode is bigger than distant accommodation mode, it is unbeneficial when wind power accommodated locally. c) The power parallel angle fluctuation increased with the increase of wind power capacity, the addition of the wind power has a certain effect on the power angle fluctuation of the system.
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