Analysis the Inertia Modeling and Stability of Brushless Doubly-Fed Induction Generator of Wind Power Grid

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Abstract

Brushless doubly-fed induction generator (BDFIG) leave out the slip ring and brush as the dual-stator structure, which can improve the reliability, reduce maintenance costs and expect to be widely used in wind power system. The current converter is installed in the one of the dual stator winding: control winding (CW), then the motor rotor is linked together with the wind turbines. The mechanical and electric inertia have different with the doubly-fed induction generator (DFIG) because of the special structure and these features directly affect the stability of power system. On the establishment and qualitative analysis of the inertia models of single and group motors of BDFIG, the vector control (VC) of the small signal model is established to solve the eigenvalue for quantitative analysis of the stability of the wind power system connected to the grid, and compared with squirrel-cage asynchronous induction generator (SCAIG), DFIG and permanent magnet synchronous generator (PMSG) to analyze the different effects on the stability of the power system. The simulation results prove the correctness of the model.

Keywords: Brushless doubly-fed induction generator (BDFIG); Dual-stator structure; Inertia model; System equivalent inertia; Stability of power system

1. INTRODUCTION

With the increase of permeability of wind power in the power grid especially in wind-rich regions, the new challenges to the safe operation of power system will appear. How to make the wind farm has the capability of traditional power plants for the regulation of power grid, called "wind power grid friendly", is an important issue for the sustainable development of wind power industry.

Doubly-fed induction generator (DFIG) has become the main types of large wind farms, which use the inverter jointing the rotor side to realize variable speed constant frequency control of wind turbines and capture the maximum wind energy. However, the power electronic converters make the decoupling relationship between the speed of wind turbine and power grid frequency. Its rotational kinetic energy was "hidden" and almost no contribution to the moment of inertia of the power system (Li et al., 2013; Li et al., 2012; Li et al., 2015; Puglisiet al., 2016).

The stator of BDFIG is made with the power winding (PW) and control winding (CW), there no direct magnetic coupling between the two windings and through the special design the rotor can be magnetic coupled respectively with the PW and CW. Hence even absence of brush and slip ring, the machine still can realize control. In recent years, particularly due to the high reliability and low maintenance cost, the BDFIG has been widely attention and expected to be widely used in wind power system (Tohidiet al., 2012; Chen et al., 2016; Pablo et al., 2015).
Literature (Li, 2014) analysis and obtained the BDFIG mathematical model of current, active power, reactive power, the electromagnetic torque, power factor, however didn't analysis the system dynamics model; Literature (SLOOTWEG, 2003) established the small signal model, and studied the stability of the cage rotor BDFIG, but didn't analysis the generation mode; Literature (Huang, 2002; Chi, 2007) studied the influences of large-scale wind power access to power system. Assuming a sample system, which access 100 MW doubly-fed wind farm in the terminal of the power grid, studied the dynamic behavior of the system, then replaced the conventional synchronous power plant of the same size to analysis, but research is limited to DFIG.

BDFIG and DFIG have some similar electrical properties, but different in the structure, and have different influence on power system (Tohidi, 2014; Longet al., 2013). The rotor side converter of DFIG realize variable speed constant frequency yet decoupling the rotor and system frequency (Zhang, 2013; Fakhari, 2013; Muljadi, 2007) The stator winding connection device of the converter of BDFIG have the same effect of variable speed constant frequency and the rotor is connected to the system, the system of inertia support can still reflect. According to the above problems, if the BDFIG applied in power system, the inertia analysis is different with DFIG and need to analysis separately.

2. THE MECHANISM OF LOW FREQUENCY OSCILLATION

2.1 The mechanism of negative damping

The mechanism of negative damping shows that the primary cause of the system low frequency oscillation is insufficient damping of the system. Because of the negative damping due to the increase in system of excitation regulator magnification offset the positive damping in the system, excitation winding and mechanical. When the system encounter the large or small disturbances, the system will be happened to the oscillation due to the small or negative damping of system.

Single - infinity system generator torque balance equation as follows:

\[ M \frac{d^2 \delta}{dt^2} + D \frac{d\delta}{dt} + P_e = P_M \] (1)

Where \( M \) is the inertial time constant, \( \delta \) is the phase angle for the rotor of the generator, \( D \) is the damping coefficient of the generator and it is a constant related to the generator and system, \( P_e \) is the necessary synchronous torque of the system to keep the generator operation.

When the small disturbances occurs, the phase angle changes from \( \delta_0 \) to \( \delta_0 + \Delta \delta \), the speed of rotor also changes from \( \omega_0 \) to \( \omega_0 + \Delta \omega \), the equations are:

\[ M \frac{d^2 \Delta \delta}{dt^2} + D \frac{d\Delta \delta}{dt} + K \Delta \delta = P_M \] (2)

The solution of equation are three kinds of situations:

(1) \( D \geq 0, \ K \geq 0 \)
\[
\Delta \delta = Ae^{-\xi \omega} \sin \sqrt{1-\xi^2} \Omega t \ , \Omega = \sqrt{\frac{K}{M}} ,\text{damping ratio } \xi = \frac{D}{2\Omega M}, \text{for } \Omega \geq 0, \ M \geq 0. \text{After the transient disturbance removal, } \Delta \delta \text{ and } \Delta \omega (\Delta \omega = \frac{d \Delta \delta}{dt}) \text{ will decay to zero, the system is stable.}
\]

(2) \( D > 0, \ K < 0 \)

\[
\Delta \delta = A_1 e^{p_1 t} + A_2 e^{p_2 t} , \text{where } p_{1,2} = \frac{1}{M} (-D \pm \sqrt{D^2 - 4KM}) ,\text{one root is positive, then } \Delta \delta \text{ with increasing aperiodically until out of step.}
\]

(3) \( D < 0, \ K < 0 \)

\[
\Delta \delta = Ae^{-\xi \omega} \sin \sqrt{1-\xi^2} \Omega t \ , \ D < 0, \text{so } \xi < 0, \Delta \delta \text{ will increase periodically until out of step.}
\]

The case is lack of the system damping torque of supporting system stability and eventually lose stability.

In conclusion, has enough synchronous torque and damping torque is necessary condition to guarantee system stable operation.

2.2 The oscillation frequency and damping ratio

The frequency of oscillation modes can be calculated through the imaginary part of the eigenvalues and the oscillation mode damping ratio can be calculated through the real component, in case the eigenvalue real part is negative. The damping ratio of the model is positive, on the contrary, the eigenvalue is positive, the system damping ratio is negative, according to the theory of negative damping, when the system happens the disturbances will lead to the oscillation.

The complex eigenvalue of characteristic equation are \( \lambda = \sigma + j\omega \). The oscillation frequency are \( f = \omega / 2\pi \), damping ratio are \( \xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \), the complex eigenvalue real part reflects the attenuation oscillation after system disturbance, Imaginary part reflects the oscillation frequency. According to the theory of weak damping, the mode stability of oscillation can assessment from the damping ratio. When the damping ratio is zero or very small positive real numbers, the system have the unstable factors. When the system is disturbed, it may cause low-frequency oscillation.

Damping ratio reflects the vibration attenuation performance in time domain. If the damping ratio is less than zero, the system is considered as negative damping and the system is unstable. The damping is considered as weak when damping ratio is in the range of 0-0.02. Usually, the damping characteristics with the damping ratio is greater than 0.04 or 0.05. The system prone to low frequency oscillation phenomena under the large or small disturbances with the negative damping or weak damping electromechanical oscillation mode.

3. THE MODEL OF THE SYSTEM EQUIVALENT INERTIA OF BDFIG

3.1 The electromagnetic relation model of BDFIG
The mathematical model of BDFIG model under dq frame system:

\[
V_p = R_p I_p + \frac{d\varphi_p}{dt} + j\omega_p \varphi_p \\
\varphi_p = L_p I_p + L_p i_r \\
V_c = R_c I_c + \frac{d\varphi_c}{dt} + j(\omega_c - (p_p + p_r)\omega_e) \varphi_c \\
\varphi_c = L_c I_c + L_c i_r \\
V_s = R_s I_s + \frac{d\varphi_s}{dt} + j(\omega_s - p_s \omega_r) \varphi_s \\
\varphi_s = L_s I_s + L_s i_r 
\]

(3)

The subscript p, c, r indicate the variables of power side, control side and rotor side respectively.

The motor of the electromagnetic torque expression is:

\[
T_e = p_p L_{pe} (i_q i_{rd} - i_p i_{rq}) + p_c L_{ce} (i_q i_{rd} + i_d i_{rq}) 
\]

(4)

The equation of motion is:

\[
(J_p + J_c) \frac{d\omega_c}{dt} = T_e - (F_p + F_c)\omega_r - T_L 
\]

(5)

3.2 The electromagnetic relation model of BDFIG

According to the former section can find that the inertia of the BDFIG is the sum of the power and control sub-motor, and no hidden kinetic energy due to the motor rotor directly connected with the draft, according to the kinetic energy formula available(Ganzha,2000):

\[
E_k = \int(P_m - P_e) dt = \int(J_p + J_c)\omega_m d\omega_m = \frac{1}{2} (J_p + J_c)\omega_m^2 = \frac{(J_p + J_c)\omega_e^2}{2(p_p + p_r)}
\]

(6)

Where \(\omega_m\), \(\omega_e\)are the mechanical angular velocity and synchronous electrical angular velocity of motor respectively, \(Jp\)and \(Jc\)are the rotational inertia of the motor and the pole pair numbers, subscribe 1 and 2 are indicate power side and control side.

A single BDFIG inertia time constant is defined as:

\[
H = (J_p + J_c)\omega_e^2 / S_N
\]

(7)

Then, The inertial time constant for the power system contain the wind BDFIG is:

\[
H_{tot} = \left[ \sum_{i=1}^{n} \left( \frac{1}{2}J_i\omega_e^2 \right) + \sum_{j=1}^{m} E_{K_{BDFIG,j}} \right] / S_{N_{tot}}
\]

(8)

Where \(n,m\)are the number of synchronous generator and BDFIG, \(J_i,p_i\)are the rotational inertia of the synchronous generator and pole pairs number respectively, \(S_{N_{tot}}\)is the total rated capacity,\(E_{K_{BDFIG,j}}\)is The rotational kinetic energy of the unit \(J\) of BDFIG.
Through the equation (8) can analyze the inertial time constant of BDFIG is larger than the single conventional asynchronous generator.

Inertia M, also known as the machine start time TM, defined as rated torque to the rotor speed from 0 to the time required to rated speed, generally, \( M = 2H \).

The relationship between the single machine inertia and the system inertia is:

\[
M_M = \frac{1}{P_M} \sum M_j P_j
\]  

(9)

Where \( M_j, M_M \) are one unit and the system equivalent inertia respectively, \( P_j, P_M \) are the generating capacity of each unit and the equivalent system.

From the expression of inertia can be seen that the system equivalent inertia is decided by the active power of the generator and the single machine inertia. Therefore, the effect on the system equivalent inertia can be analyzed by the single inertia and the active outputs.

4. THE MODEL AND ANALYSIS OF THE SYSTEM EQUIVALENT INERTIA

4.1 The effect on the system equivalent inertia by the single machine inertia

According to the models of the single and system equivalent inertia can find that the system equivalent inertia is decided by unit inertia and the system active output. When large-scale wind power connected to the electricity grid, conventional generating units will be replaced partly by the wind generators. If the inertia of wind turbines is differ from the conventional power generations, the effect on the system inertia will magnify with the wind capacitance increases. Then firstly need to analysis of wind power unit inertia for studying the effect on the system inertia after large-scale wind power access.

If (7) split into the model of system equivalent inertia, then

\[
M' = \frac{1}{P_1 + \Delta P} (M_1 P_1 + M_{BDFG} \Delta P)
\]  

(10)

Where \( M \) is the system equivalent inertia after access to the wind power, \( M_1 \) is the original system equivalent inertia, \( P_1 \) is the original system output, \( \Delta P \) is the capacity of wind power, \( M_{BDFG} \) is the inertia of BDFIG.

Considering (10) can derive that if \( \Delta P \) and \( P_1 \) are same orders of magnitude, then the system equivalent inertia is increase and the system stability is improved after access to the wind power.

4.2 A single unit output effect the equivalent moment of inertia of the system

When the wind power output of generating is changed, the system equivalent inertia is:

\[
M' = \frac{M_1 P_1 + M_{BDFG} \Delta P}{P_1 + \Delta P_1} = M_1 - \frac{\Delta P_1 (M_1 - M_{BDFG})}{P_1 + \Delta P_1}
\]

(11)

Where \( \Delta P_1 \) is the increased output of wind turbines.
Considering (11) can derive that the output of BDFIG is increased, the system equivalent inertia is also increased, and also enhance the stability of the system.

4.3 The analysis of the system equivalent inertia of access to the wind farm

4.3.1 The equivalent model of wind farms

Because of the wind turbine capacity is small, when large-scale wind power connected to the power grid, wind farm composed of tens or even hundreds of typhoon electric machines. If the study of large-scale wind, the wind generator can ignore the internal model in detail and are equivalent to the several wind turbines access the system by parallel. If the same type of wind turbines work in a wind farm under the same wind conditions, then can equivalent to a unit one, formulas of its impedance are (Guan, 2008):

\[
\begin{align*}
    r_n &= \frac{r}{n} \\
    x_n &= \frac{x}{n}
\end{align*}
\]

(12)

Where \( r \) is the resistance of one wind turbine before equivalent, \( x \) is reactance of one wind turbine before equivalent, \( r_n \) is the equivalent resistance of wind power system, \( x_n \) is the equivalent reactance of wind power system.

The radius of wind farms equivalent model is:

\[ R_{eq} = \sqrt{nR} \]  \hspace{1cm} (13)

Where \( R \) is the radius of one wind turbine before equivalent.

The equivalent inertia model of wind farms is:

\[ M_{eq} = \frac{\sum_{i=1}^{n} M_i S_i}{\sum_{i=1}^{n} S_i} \]  \hspace{1cm} (14)

Where \( S \) is the capacity of one wind turbine before equivalent. If the same types of wind turbines work in a wind farm under the same wind conditions, the wind power equivalent inertia is equal to the inertia of a single machine.

When the large-scale wind farms access to the power system and the generators are BDFIG, the system equivalent inertia is:

\[ M'_{eq} = \frac{1}{P_i + \Delta P} (M_i P_i + M_{eq} \Delta P) \]  \hspace{1cm} (15)

Considering (15) can derive that the wind power grid capacity is bigger and the influence on system equivalent inertia is larger. Meanwhile, the system equivalent inertia changes with the output changes.

4.4 The relationship between the damping characteristics and small signal stability
Based on the negative damping theory that when the system damping ratio is very weak or negative, the system disturbance, big or small can lead to growth or oscillation damping. So in the eigenvalue analysis method, used damping ratios measure the dynamic characteristics of system. The better the damping ratio, the greater the small signal stability, the system equivalent inertia and network is closely related to the small signal stability, the greater the system equivalent inertia, the higher the power grid small disturbance stability. There can be seen from the above analysis, the BDFIG connected to the electricity grid, the system equivalent inertia increased compared to the original system, means that the small disturbance stability improved. Through the small signal model calculation eigenvalue can further quantitative analysis the influence of small disturbance to the system after connected to the system.

5. THE SMALL SIGNAL MODEL OF FLUX ORIENTED VECTOR CONTROL OF BDFIG

When BDFIG receives little disturbance, the equations are nonlinear (Li,2013). Linearized the equation (1)~(3) can get the small signal model shown in (14), where \( \Delta \) indicates small incremental, the subscript 0 indicates the steady-state value and can be obtained by steady state equation, superscript ‘ indicates the value convert to the power winding.

\[
\begin{align*}
\Delta V_{pr} &= \left[ R_p + pL_{pr} \right] \Delta i_{pr} - \omega_p L_{pr} \Delta \phi & & 0 \quad 0 \quad pL_{pr} \quad -\omega_p L_{pr} \quad 0 \\
\Delta V_{i} &= \left[ R_i + pL_{i} \right] \Delta i_{i} - \omega_i L_{i} \Delta \phi & & 0 \quad 0 \quad k_{qi} \quad k_{qi} \quad 0 \\
\Delta V_{c} &= 0 \quad 0 \quad \left[ R_c + pL_{c} \right] \Delta i_{c} \quad k_{qi} \quad R_p + pL_{pr} \quad k_{qi} \quad L_{pr} \quad k_{qi} \quad 0 \\
\Delta V_{d} &= pL_{pr} \quad k_{qi} \quad R_p + pL_{pr} \quad k_{qi} \quad R_p + pL_{pr} \quad k_{qi} \quad L_{pr} \quad (L_{pr} + L_{pr} + L_{pr}) \rho_p \\
\Delta V_{e} &= k_{qi} \quad pL_{pr} \quad k_{qi} \quad R_p + pL_{pr} \quad k_{qi} \quad R_p + pL_{pr} \quad (L_{pr} + L_{pr} + L_{pr}) \rho_p \\
\Delta T_r &= -p_{d}L_{r} \Delta i_{d} - p_{d}L_{r} \Delta i_{q} - p_{d}L_{r} \Delta i_{d} - p_{d}L_{r} \Delta i_{q} - p_{d}L_{r} \Delta i_{d} - p_{d}L_{r} \Delta i_{q} \quad (p_{d}L_{r} \Delta i_{d} + p_{d}L_{r} \Delta i_{q}) \quad 0 \\
\Delta T_q &= -p_{d}L_{r} \Delta i_{d} - p_{d}L_{r} \Delta i_{q} - p_{d}L_{r} \Delta i_{d} - p_{d}L_{r} \Delta i_{q} - p_{d}L_{r} \Delta i_{d} - p_{d}L_{r} \Delta i_{q} \quad (p_{d}L_{r} \Delta i_{d} + p_{d}L_{r} \Delta i_{q}) \quad 0 \\
\end{align*}
\]

Due to the grid power winding is connected to a power grid and can be taken for the grid voltage does not change. So can get: \( \Delta V_{pr}=0 \), meanwhile the voltage of rotor is zero, means \( \Delta V_{qr}=0, \Delta V_{eq}=0 \).

Different working mode and control mode can form different small signal models. This paper studies the generator model of PW flux vector orientation, means \( |\varphi_{pd}| = |\varphi_{qr}| = 0 \), Control block diagram see literature (Shao,2009).The inputs of control system are drag torque and rotational speed, the state variables are \( i_{pd}, i_{pq}, i_{d}, i_{q}, i_{ca}, i_{qa}, u_{ca}, u_{qa}, \omega_r, \theta \), the control winding voltage is:

\[
\begin{align*}
\dot{i}_{ca} &= \frac{r_e (L_e L_{\sigma_p} - L_{\sigma_q}^2)}{r_e L_{\sigma_p}} (i_{ca} - \dot{i}_{ca}) + \int r_e (i_{ca} - \dot{i}_{ca}) dt + D_{ca} \\
\dot{i}_{qa} &= \frac{r_e (L_e L_{\sigma_p} - L_{\sigma_q}^2)}{r_e L_{\sigma_p}} (i_{qa} - \dot{i}_{qa}) + \int r_e (i_{qa} - \dot{i}_{qa}) dt + D_{qa}
\end{align*}
\]

Where \( D_{ca}, D_{qa} \) are disturbers terms of PI regulators, detail can be found in Appendices, it can be ignorant if the PI parameters set reasonably. Then can get:

\[
\begin{align*}
\rho \Delta i_{ca} &= \frac{r_e (L_e L_{\sigma_p} - L_{\sigma_q}^2)}{r_e L_{\sigma_p}} (\rho \Delta i_{ca} - \rho \Delta i_{ca}) + \int r_e (\Delta i_{ca} - \Delta i_{ca})dt \\
\rho \Delta i_{qa} &= \frac{r_e (L_e L_{\sigma_p} - L_{\sigma_q}^2)}{r_e L_{\sigma_p}} (\rho \Delta i_{qa} - \rho \Delta i_{qa}) + \int r_e (\Delta i_{qa} - \Delta i_{qa})dt
\end{align*}
\]
Meanwhile,

\[
\begin{align*}
\rho \Delta i_{cd}^{ref} & \approx -i_{cq0}^{ref}(P_p + P_c)\Delta \omega, \quad \rho \Delta i_{cq}^{ref} \approx -i_{cd0}^{ref}(P_p + P_c)\Delta \omega, \quad \rho \Delta i_{cd} \approx -i_{cq0}^{ref}(P_p + P_c)\Delta \omega, \\
\rho \Delta i_{cq} & \approx i_{cd0}(P_p + P_c)\Delta \omega, \quad \Delta i_{cd}^{ref} \approx -i_{cq0}^{ref}(P_p + P_c)\Delta \theta, \quad \Delta i_{cq} \approx i_{cd0}(P_p + P_c)\Delta \theta.
\end{align*}
\]

Split into (15):

\[
\begin{align*}
\rho \Delta i_{cd} &= \frac{r_c(L_c L_q \sigma_c - L_c^2)}{r_c L_q \sigma_c} (P_p + P_c)\Delta \omega (i_{cq0} - i_{cq0}^{ref}) + \frac{r_c}{r_c L_q \sigma_c} (P_p + P_c)\Delta \theta (i_{cq0} - i_{cq0}^{ref}) \\
\rho \Delta i_{cq} &= -\frac{r_c(L_c L_q \sigma_c - L_c^2)}{r_c L_q \sigma_c} (P_p + P_c)\Delta \omega (i_{cd0} + i_{cd0}^{ref}) - \frac{r_c}{r_c L_q \sigma_c} (P_p + P_c)\Delta \theta (i_{cd0} - i_{cd0}^{ref})
\end{align*}
\]

According to the equation (16) of the linearized model can get small signal model of the PW flux orientation, the state variables are \([\Delta i_{pd}, \Delta i_{pq}, \Delta i_{d0}, \Delta i_{q0}, \Delta U_{d}, \Delta U_{q}, \Delta U_{d0}, \Delta U_{q0}, \Delta \omega, \Delta \theta]^T\), input variables are \(0, 0, 0, 0, 0, 0, 0, 0, 0, 0\), the standard form is:

\[
\Delta x = A\Delta x + B\Delta u \quad (20)
\]

6. THE ANALYSIS OF SMALL SIGNAL STABILITY AND DISCUSSION OF THE RESULTS OF SIMULATION

The stability problem of the BDFIG can be divided into static and dynamic stability. Static stability is the problem of whether can keep pace and stable operation under the small disturbance. Dynamic stability is the problem of whether can keep pace and stable operation under a big change in the operation process. Because the generator can't work more than the static stability limit but could still work more than dynamic stability limit, so here only to discuss the static stability problems of BDFIG(Xiong,2010).

According to the small signal model, the stable operation condition can obtain by lyapunov stability criterion. According to the linear system theory and lyapunov stability criterion, the system is asymptotically stable as long as the pole of linear time-invariant matrix A have the negative real component and then judge the lyapunov stability of linear time-varying systems under periodic changes (Xie,2015).

6.1 The simulation results

6.1.1 The profile the simulation model

This paper adopts the model of Hexi power grid in the literature (Li,2013).The grid is located in Gansu province which is the center of the northwest electric power transmission and exchange. Hexi power grid is located in the west of Hexi corridor in Gansu province shown in figure 1, the most of the wind power are send to Lanzhou 1000 kilometers away by the normal way. The Jiuquan wind power base is the one of the most largest concentrated interconnection in the world, is the one of the biggest concentrated grid, sends out the farthest distance to transport, and the highest voltage level of collection and delivery.

Using the Hexi power grid as the research object, this paper studies the influence of small signal stability after large-scale wind power access to power grid. Based on the
former analysis of the relationship between the system equivalent inertia and grid damping characteristics can get the system single inertia and active output to the system equivalent inertia.

From the system inertia model can analyze the effect on the system equivalent inertia through the dominant oscillation mode after the large scale wind power access to power grid.

The simulate calculation uses inverse iteration Rayleigh quotient iteration method, the starting point of real component is zero, the imaginary part is 0.628, the finish real component is 0, the imaginary part is 15.7, the initial iteration number 10, the number of iterations up to 200, allowance error is $10^{-6}$, each turn can obtain the 10 eigenvalues. The simulate condition is the small winter operation mode of 2011 and wind power output are 1820 MW in hexi area.

6.1.2 The process simulation and calculation

6.1.2.1 The analysis of influence of the different type for wind turbine

Literature (Li,2013) calculated and analyzed the influence of on the power grid after access the wind power of squirrel-cage asynchronous induction generator (SCAIG), doubly-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG), according to the analysis calculate the small disturbance of BDFIG based on the simulation conditions:

![Diagram of Hexi power grid wind farms](image)

**Figure 1.** The diagram of Hexi power grid wind farms

<table>
<thead>
<tr>
<th>The type of generator</th>
<th>Mode</th>
<th>Real part</th>
<th>Imaginary part</th>
<th>Frequency</th>
<th>Damping ratio</th>
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The relationship of damping ratio and type of wind turbines are shown in the following figure 2.

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DFIG

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PMSG

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<th>5.90</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.41236</td>
<td>6.64758</td>
<td>1.060</td>
<td>5.90</td>
</tr>
<tr>
<td>2</td>
<td>-0.00724</td>
<td>10.76382</td>
<td>1.7234</td>
<td>0.0732</td>
</tr>
<tr>
<td>3</td>
<td>-0.34251</td>
<td>4.78473</td>
<td>0.58932</td>
<td>8.4675</td>
</tr>
<tr>
<td>4</td>
<td>-0.18294</td>
<td>3.56274</td>
<td>0.87294</td>
<td>3.8927</td>
</tr>
</tbody>
</table>

The relationship of damping ratio and type of wind turbines are shown in the follow figure 2.

Figure 2. The relationship of damping ratio and type of wind turbines

From the calculation results can be seen that the system equivalent inertia of BDFIG is the biggest and best damping characteristics, the second is SCAIG, then is DFIG, and the system equivalent inertia of PMSG is the minimum, the small signal stability of power grid is the worst. The results also verified the relationship between the system equivalent inertia and the system damping ratio is correct, the smaller the system equivalent inertia, the worse the small signal stability.

6.1.2.2 The impact analysis of wind farm output of power grids

6.1.2.2.1 The simulation conditions

This paper selects the small load operation mode winter in 2012, the wind power output set from 0% to 60%, then calculate and analyze of the relationship between the wind power output of 0, 20 %, 40% and 60% with the system inertia and small perturbation. Set four kinds of wind power output can obtain:
Table 2: The eigenvalue of different wind power output of corresponding oscillation model

<table>
<thead>
<tr>
<th>Wind power output ratio</th>
<th>Mode</th>
<th>Real part</th>
<th>Imaginary part</th>
<th>Frequency</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>1</td>
<td>0.364</td>
<td>4.279005</td>
<td>0.681025</td>
<td>0.8521</td>
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<tr>
<td></td>
<td>2</td>
<td>-0.729679</td>
<td>8.894783</td>
<td>1.415649</td>
<td>8.176</td>
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<tr>
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<td>3</td>
<td>-0.730932</td>
<td>10.763464</td>
<td>1.713059</td>
<td>6.7753</td>
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<tr>
<td></td>
<td>4</td>
<td>-6.84E-004</td>
<td>13.85734</td>
<td>2.20546</td>
<td>0.0049</td>
</tr>
<tr>
<td>20%</td>
<td>1</td>
<td>0.000023</td>
<td>4.276451</td>
<td>0.67384</td>
<td>0.7632</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.00015</td>
<td>8.97463</td>
<td>1.47873</td>
<td>8.02634</td>
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<tr>
<td></td>
<td>3</td>
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<td>10.87463</td>
<td>1.73625</td>
<td>6.65743</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.00037</td>
<td>13.80294</td>
<td>2.19723</td>
<td>0.00382</td>
</tr>
<tr>
<td>40%</td>
<td>1</td>
<td>0.000567</td>
<td>4.76453</td>
<td>0.69362</td>
<td>7.8735</td>
</tr>
<tr>
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<td>2</td>
<td>-0.00034</td>
<td>8.84373</td>
<td>1.48372</td>
<td>6.2636</td>
</tr>
<tr>
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<td>3</td>
<td>-0.00037</td>
<td>10.54637</td>
<td>1.73272</td>
<td>0.00278</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.00049</td>
<td>13.67257</td>
<td>2.16327</td>
<td>0.0020</td>
</tr>
<tr>
<td>60%</td>
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<td>0.006183</td>
<td>4.264271</td>
<td>0.67902</td>
<td>-0.145</td>
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<tr>
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<td>-0.67261</td>
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</tr>
<tr>
<td></td>
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<td>6.0016</td>
</tr>
<tr>
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<td>4</td>
<td>-0.00111</td>
<td>13.89463</td>
<td>2.21521</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

The relationship of damping ratio and type of wind power percent are show in the follow figure 3

![Figure 3](image-url)

**Figure 3.** The relationship of damping ratio and type of wind power percent

From the results can see that the damping ratio continues to decrease when wind power output increases, means that the large-scale wind power access the grid intensively, due to the small inertia of wind power, the system equivalent inertia is relatively weak with the increase of wind power output. If the level of wind power output is higher, the damping of grid even becomes negative and affect the stable operation of power system.
7. CONCLUSION

The single machine inertia model is deduced based on the electromagnetic model of BDFIG and get the system equivalent inertia according to the single inertia and active power output. Then the flux orientation vector control of small signal mode is established. Based on this model small disturbance characteristic root of the system can be calculated and analysed the stability of wind power generation system by using lyapunov stability theorem. Specific as follows:

(1) The special physical structure of BDFIG improves the inertia characteristics of wind turbine, which makes the BDFIG has a certain supporting function to the stability of the power grid, and verify the conclusions by compared with the SCAIG, the DFIG, the PMSG;

(2) Through the eigenvalue by the small signal model of the quantitative calculation and comparison with the SCAIG, the DFIG concluded that different wind turbine had the different affection on the small disturbance stability of power grids, and is verified the different effect on the stability of the power grid when the mass concentration of different output. The study have the practical significance especially to the weak network of northwest power grid, and is a beneficial attempt for wind power system stability research.

Considering the limitations of present study condition, there has been no prototype experiments, in the future work is proposed to do experiments on the above conclusion, further in-depth study the inertia characteristic of BDFIG and the grid frequency stability mechanism and improvement measures.

8. ACKNOWLEDGMENTS

This work was supported by the Natural Science Foundation of China (51467018)

9. REFERENCE:


**APPENDIX**

\[
D_a = \frac{r_{sd}L_p}{L_p L_s} i_{sd} - Pr\varphi_p - \frac{L_p}{L_p L_s} \varphi_p \left( \frac{L_s}{L_p} - \frac{1}{\sigma_p} \right) \varphi_p + \left( \varphi_p - P P \omega \right) \frac{L_p^2}{L_s} \varphi_p - \left( \varphi_p - P P \omega \right) L_s \varphi_p \left( i_{d} \right)
\]

\[
D_q = \frac{r_{sd}L_p}{L_p L_s} i_{sd} + Pr\varphi_p + \frac{L_p}{L_p L_s} \varphi_p \left( \frac{L_s}{L_p} - \frac{1}{\sigma_p} \right) \varphi_p + \left( \varphi_p - P P \omega \right) \frac{L_p^2}{L_s} \varphi_p - \left( \varphi_p - P P \omega \right) L_s \varphi_p \left( i_{q} \right)
\]
Where $L_{sp}$, $L_{sc}$ are the self-inductance of PW and CW respectively, $L_{pr}$, $L_{cs}$ are the mutual-inductance of PW and CW respectively, $\sigma_p = 1 - \frac{L_{pr}^2}{L_{sp}L_{cs}}$. 