Study of Power System Oscillation with Wind Power Equipping Frequency Regulation

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Abstract. As more and more countries and regions stipulate that wind farms need to have frequency regulation, especially in the power grid with high proportion of wind power. It’s very clear that frequency regulation can improve the frequency dynamic of power system, but the influence of frequency regulation on power system oscillation is uncertain. This paper focuses on this influence and presents a linearized model to analyze the participation of the factors. In the end, a case system named four machine two area system is applied in the simulation to verify the validity of the model.

1. Introduction

In recent years, the wind power is becoming more and more popular around the world. Wind power has deeper and deeper impact on the safety and stability of the power system. The increase of wind power penetration reduces the reserve capacity of power system for frequency support, which makes the grid frequency change more rapidly and unpredictably when frequency events occur. Therefore, according to the grid codes issued by many countries and regions, wind turbines (WTs) need to provide frequency regulation for the power system.

Much research has been done on the issue of power system oscillation when the WTs are equipped with frequency control. Reference [1] gives an overall overview on multi-frequency oscillations that may happen with a high wind power penetration. Reference [2] sees traditional WTs frequency regulation as a PD controller of frequency, and proposes a method to introduce a positive damping to the system which adds a first-order lag segment to the controller. Reference [3] focuses on PMSG-based WTs, and puts forward a control scheme called optimized power point tracking (OPPT), which could break the negative relationship between inertia control and power system damping and achieve smooth recovery while suffering frequency deviation. Reference [4] offers a control scheme with fuzzy logic to avoid inter-area oscillation as well as provide system fast frequency response. Reference [5] states that
a new power oscillation against the synchronous machine in the same region is induced by the windfarms’ inertia control and introduces a kind of damping controller based on active power modulation.

Although a large number of studies have been done on the mechanism and suppression method of power system low-frequency oscillation, there is little research on the influence of frequency regulation on it. Taking the GE DFIG-based WT as an example, this paper analyzes the influence of frequency regulation of WT on power system low-frequency oscillation. By developing the four-machine two-area system, the impact mechanism of it is given.

2. Modelling of DFIG-based WT

2.1. Overall control Schemes of DFIG-based WT

![Diagram of Control Scheme of DFIG-based WTs]

Figure 1. Control scheme of DFIG-based WTs

In this paper, the DFIG-based WT of GE is taken as an example [7]. The control system of a DFIG-based WT mainly includes the turbine control and the converter control as shown in Figure 1. They act in different time scales to give system frequency support. The turbine control is constituted of the speed control and the pitch control. When there is no primary frequency control, speed control and pitch control make sure that maximal wind energy is captured and pitch control limit the captured power ensuring that WT works at a safe operation point. The input of the converter control, i.e., the electromagnetic torque reference, is obtained from the turbine control. The rotor-side converter control
system determines the electromagnetic torque and the reactive power of DFIG-based WT, and it gives rotor current reference to following control model. The electromagnetic torque reference of conventional DFIG-based WT usually comes from the speed control.

In addition, frequency control is added according to the grid requirements, which includes inertia control (IR) and primary frequency control (PFC). Inertia control takes the change rate of frequency as the input and passes through a low-pass filter, which could be seen as a high-pass filter together. The PFC of DFIG-based WT takes the frequency deviation as the input. The output changes along with the input changes. The output gives the power reference of pitch compensation. Therefore, the output power of DFIG-based WT is changed as the pitch angle is adjusted when the system frequency varies.

2.2. Small-signal modelling of DFIG-based WT

The DFIG-based WT system exists several nonlinear portions. A linearized model is needed for using typical small-signal analysis techniques. In this paper, all variables are in per-unit forms and the motor convention is adopted. For simplifying the analysis, the following assumptions are made:

1) Wind speed is constant.
2) The stator transients and stator resistance are neglected.
3) Since the issue analyzed in this paper mainly deals with power flows in slow time-scale, transient dynamics of rotor-side current control and grid-side control are neglected, which means rotor current follows the control in this time-scale closely. After that, the reactive control loop is also ignored.
4) The PFC operation point is outside the deadband and inside the amplitude limit.
5) Compared with electric-mechanical timescale control, the typical bandwidth of the PLL is relatively high in order to track the phase of power system. So this fast dynamic is negligible. Under that assumption, its’ output nearly equals to angle frequency of the power grid.

In the following part subscript ‘0’ represents the value in the steady state.

2.2.1. Rotor model

The physical relation about rotor is:

\[ P_{m} - P_{e} = 2H\omega_{r} \frac{d\omega_{r}}{dt} \]

After linearization:

\[ \Delta P_{m} - \Delta P_{e} = 2H\Delta\omega_{r} \frac{d\omega_{r}}{dt} \bigg|_{\omega_{r}=\omega_{r0}} + 2H\omega_{r0} \frac{d\Delta\omega_{r}}{dt} \approx 2H\omega_{r0} \frac{d\Delta\omega_{r}}{dt} \] (2)

2.2.2. Wind power model

The physical relation about wind power model is:

\[ P_{m} = k_{w} v_{w}^{3} C_{p}(\lambda, \beta) \] (3)

After linearization:

\[ \Delta P_{m} = k_{\omega} \Delta\omega_{r} + k_{\beta} \Delta\beta \] (4)

Coefficients in (4)

\[ k_{\omega} = k_{w} v_{w}^{3} \left. \frac{\partial C_{p}(\lambda, \beta)}{\partial\lambda} \right|_{\lambda=\lambda_{0}, R: V_{e}} \]

\[ k_{\beta} = k_{w} v_{w}^{3} \left. \frac{\partial C_{p}(\lambda, \beta)}{\partial\beta} \right|_{\beta=\beta_{0}} \]
2.2.3. *maximum power point tracking (MPPT) model*

When equipped with PFC, WTs are required to deload a portion of output, often 10%. So the parameters in this model are under deloading condition.

The physical relation about MPPT model is:

\[
\omega_{ref} = aP_c^2 + bP_c + c
\]  
\[(5)\]

\(a\), \(b\) and \(c\) are all coefficients.

After linearization:

\[
k_{MPPT} = 2aP_{in} + b
\]  
\[(6)\]

The typical values of \(a\), \(b\) and \(c\) are -0.67, 1.42, 0.51.

2.2.4. *Stator voltage equation*

Ignoring the magnitude dynamic of stator flux, the model of stator voltage is as follows:

\[
U_s = R_s I_s + j\omega L_s
\]  
\[(7)\]

2.2.5. *Rotor-side converter equation*

Based on stator voltage-oriented control, the rotor voltage and flux equations are as follows:

\[
u_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} - \omega_{slip} \psi_{rq}
\]  
\[(8)\]

\[
u_{rq} = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \omega_{slip} \psi_{rd}
\]

\[
\psi_{rd} = \sigma L_r i_{rd}
\]

\[
\psi_{rq} = \frac{L_m}{\omega L_s} U_s + \sigma L_r i_{rq}
\]  
\[(9)\]

in which,

\[
\sigma = 1 - \frac{L_m^2}{L_r L_s}
\]

After adding a PI controller between rotor voltage and rotor current in order to eliminate steady-state error, the form is:

\[
\begin{cases}
    u_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} - \omega_{slip} \left( \frac{L_m}{\omega L_s} U_s + \sigma L_r i_{rq} \right) + k_{pr}\left( i_{rd}^* - i_{rd} \right) + k_{pr}\int \left( i_{rd}^* - i_{rd} \right) dt \\
    u_{rq} = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \omega_{slip} \sigma L_r i_{rd} + k_{pr}\left( i_{rq}^* - i_{rq} \right) + k_{pr}\int \left( i_{rq}^* - i_{rq} \right) dt
\end{cases}
\]  
\[(10)\]

2.2.6. *Grid-side converter equation*

Based on stator voltage-oriented control, the DC capacitor voltage and grid current equations are as follows:

\[
\begin{cases}
    L_g \frac{di_{gd}}{dt} = u_{gd} - v_{gd} - R_g i_{gd} + \omega L_g i_{gg} \\
    L_g \frac{di_{gg}}{dt} = -v_{gg} - R_g i_{gg} - \omega L_g i_{gd} \\
    C \frac{dU_{dc}}{dt} = \frac{3}{2} S_d i_{gy} + \frac{3}{2} S_d i_{gd} - i_{load} 
\end{cases}
\]  
\[(11)\]
Adding a PI controller between grid voltage and grid current in order to eliminate steady-state error, the form is:

\[
L_g \frac{di_g^*}{dt} + k_{igp}(i_g^* - i_g) + k_{igl}\int(i_g^* - i_g)dt = u_{gd} - v_{gd} - R_g i_{gd} + \omega_L L_g^2 i_{gd}
\]

\[
L_g \frac{di_g^*}{dt} + k_{igp}(i_g^* - i_g) + k_{igl}\int(i_g^* - i_g)dt = -v_{gq} R_g i_{gq} - \omega_L^2 i_{gd}
\]

\[
C \frac{dU_{dc}^*}{dt} + k_{ip}(U_{dc}^* - U_{dc}) + k_{id}\int(U_{dc}^* - U_{dc})dt = \frac{3}{2} S_d i_{gq} + \frac{3}{2} S_d i_{gd} - i_{load}
\]

(12)

2.2.7. Pitch control & Pitch Compensation

Pitch angle \(\beta\) follows the equation below:

\[
\beta + T_p \frac{d\beta}{dt} = k_{pp}(\omega_r - \omega_{ref}) + k_{pp}\int(\omega_r - \omega_{ref})dt + k_{pce}(P - P_{ref}) + k_{pc}\int(P - P_{ref})dt
\]

(13)

2.2.8. Speed control & Inertia control

The reference of electromagnetic torque follows the equation below:

\[
T_{ref} = T_{eo} + T_{add} = k_{mos}(\omega_r - \omega_{ref}) + k_{mos}\int(\omega_r - \omega_{ref})dt + T_{add}
\]

\[
T_{add} + T_f \frac{dT_{add}}{dt} = K_f \frac{d(f_{ref} - f)}{dt} = -K_f \frac{df}{dt}
\]

(14)

(15)

3. Impact Analysis

The four-machine two-area system is used for the mechanism analysis of the frequency regulation on power system oscillation. As illustrated in Reference [6], there are three rotor angle modes of oscillation in the traditional four-machine two-area system, including one interarea mode and two intermachine oscillation modes. In the system shown in Figure 2, the synchronous machine G2 is replaced by a DFIG wind farm. As a result, the intermachine oscillation mode between G1 and G2 disappears. In the following analysis, the influence on the interarea mode and the intermachine oscillation mode between G3 and G4 is mainly included.

![Figure 2. The extended four-machine two-area system with wind farm](image-url)
3.1. The influence of Inertia control (IR)

Table 1 shows the change of eigenvalues of interarea mode when IR parameter varies. Compared with the case without wind farm, the eigenvalues after wind farm replacing G2 change a lot. The real part and imaginary part of eigenvalue both become larger, which means that the frequency of oscillation is higher and the damping is weaker. Moreover, it can be easily concluded that the larger the gain of IR is, the weaker the damping is.

| No wind farm | WF without IR | IR \( k_f = 10 \) | IR \( k_f = 10 \) |
|--------------|---------------|----------------|----------------|
| 0.0443±j3.59 | 0.163±j4.13   | 0.149±j4.12    | 0.136±j4.12    |

Observing the data in Table 2, it is easy to find that the WF has little influence on the intermachine mode between G3 and G4. According to Reference [6], the dominant states of this mode are the states of G3 and G4. So phenomenon that WF has no influence on this mode is reasonable. Thus, in the next part, the influence on intermachine mode between G3 and G4 is no more illustrated.

3.2. The influence of Primary frequency control (PFC)

Another important part of frequency regulation of WT is PFC. The eigenvalues shown in Table 3 represent the influence of PFC parameter on interarea mode. As the gain of PFC is turned larger, the real part and imaginary part change in a small range. Compared with the influence of IR, the influence of PFC is limited. Besides, the increase of the gain will make the damping of oscillation weaker, which is contrary to influence of IR.

| No wind farm | WF (deloading) | PFC \( k_f = 5 \) | PFC \( k_f = 10 \) |
|--------------|---------------|----------------|----------------|
| 0.0443±j3.59 | 0.164±j4.13   | 0.165±j4.18    | 0.166±j4.16    |

4. Simulation

The system for simulation is shown in Figure 2. Figure 3 and Figure 4 shows the simulation results of system frequency when there is a disturbance occurring at \( t = 100s \). As shown in Figure 3, the oscillation becomes severe when the wind farm replaces the synchronous machine G2. However, the oscillation is suppressed as the gain of IR becomes bigger. The simulation results in Figure 4 shows little difference, which represents that the PFC of WT has little effect. These simulation results verify the previous analysis.
5. Conclusion
This paper takes the GE DFIG-based WT as an example and gives the small-signal model of WT. Based on this, the impact mechanism of frequency regulation on power system oscillation is given by analyzing the extended four-machine two-area system. Therefore, the analysis shows that the inertia control has positive influence on the oscillation and primary frequency control has limited impact on it. Besides, as the gain of inertia control increases, the damping of oscillation becomes stronger. Finally, the simulation results prove the analysis.

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