The Impact of Primary Frequency Control of WTs on Ultra-Low Frequency Oscillation

Lei Yang1, Xiaojie Zhang2*, Wei Huang3, Chen Wu3, Shengnan Li1, Yixuan Chen4, Hongkai Kang2

1 Yunnan Electric Power Research Institute, Kunming, Yunnan, 650217, China
2 State Key Laboratory of Advanced Electromagnetic Engineering and Technology, and School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, 430074, China
3 Power Dispatching Center of Yunnan Electric Power Group Co., Ltd, Kunming, Yunnan, 650217, China
4 Power Planning Research Center of Yunnan Power Grid Co., Ltd, Kunming, Yunnan, 650217, China

*Corresponding author’s e-mail: xjzhang16@hust.edu.cn

Abstract. Since entering the 21st century, as wind power develops rapidly, wind power plays an increasingly important role in the safe and stable operation of power systems. Since the wind turbines under traditional control don’t provide frequency support, the frequency dynamics of the power grids after load disturbance will be deteriorated. Thus, wind farms are required to equip primary frequency control in many countries. Most existing researches on primary frequency control of wind turbines focus on control strategies and the impact on system frequency, but few studies pay attention to the impact of primary frequency control of wind power on ultra-low frequency oscillation. This paper first proposes an analysis framework for ultra-low frequency oscillations in power systems with wind power. On this basis, a motion equation model of wind turbines is established. Finally, an extended three-machine nine-node system is used as an example to analyze the impact mechanism of primary frequency control on ultra-low frequency oscillation. The impact mechanism provides reference for the design of primary frequency of wind turbines in some regional power grids with ultra-low frequency oscillation.

1. Introduction

In recent years, the worldwide wind power is developing and growing. Wind power has more and more far-reaching impact on the safe and stable operation of the power system. The increase of wind power penetration reduces the reserve capacity of power systems for frequency support, which makes the grid frequency change more rapidly when frequency events occur [1]. Therefore, according to the grid codes issued by many countries and regions, wind turbines (WTs) need to provide primary frequency control (PFC) for the power system [2].

The ultra-low frequency oscillation of less than 0.1Hz has occurred for many times in the operation of the feeder end of power network with high hydropower proportion. Much research has been done on the issue of ultra-low frequency oscillation. Reference [3] analyzes the power flow characteristics and oscillation amplitude-phase characteristics of ULFO in the Southwest Power Grid caused by
typical faults. Reference [4] infers that in the Southwest Power Grid, the higher the load level is, the more easily ULFO would happen. And it also draws a conclusion that ULFO can be easily induced by N-1 and N-2 faults. Reference [5] suggests that based on the assumption of a constant load, the state variables of power system stabilizer (PSS) and excitation system appears no influence on ULFO. Reference [6] generally analyses the effect of governor parameters in different segments under two modes and offer guidance on improving the ULFO problem. So, it is known that the most common method of improving the ULFO response is to optimize the parameters of PID controller in hydro-governor. Reference [4] and [7] give specific approach about optimizing the PID controller parameters to strike a balance between restrictions on frequency control and suppression ULFO. Reference [6] suggests that in Yunnan power grids, the parameters of governor should cope with frequency limit control (FLC) in HVDC systems and satisfy the frequency stability margin, which causes no effect on the peak value of frequency deviation.

Although a large number of studies have been done on the analysis and suppression of ultra-low frequency oscillation, there is little research on the impact of PFC on the ultra-low frequency oscillation. Therefore, taking double fed induction generator (DFIG) based WT as an example, this paper reveals the impact mechanism of wind power PFC on ultra-low frequency oscillation of power system. In order to study the impact of PFC on ultra-low frequency oscillation, the motion equation model of DFIG-based WT is proposed. Through the model, the impact mechanism of PFC on ultra-low frequency oscillation is explained, and the impact law of PFC of doubly fed wind turbine on ultra-low frequency oscillation of power system is analyzed.

2. The Ultra-Low Frequency Oscillation of Power System

In a traditional power system, the rotor inertia, governor and prime mover are mainly concerned for ultra-low frequency oscillation. An analysis model of power system with multi synchronous generations for ultra-low frequency oscillation is shown in Figure 1.

![Figure 1. The analysis model of power system with multi synchronous generations for ultra-low frequency oscillation](image)

In this model, by analyzing the zero-crossing point and phase margin of the open-loop transfer function of the system, the impact of the control parameters on the oscillation frequency and damping of the ultra-low frequency oscillation can be obtained. However, different from the synchronous machine, the frequency of the rotor and the terminal voltage frequency of the WT is not strongly coupled. The relationship between them is affected by the converter and the controller. The previous analysis model of the WT cannot be directly applied to the ultra-low frequency oscillation analysis model. Therefore, in order to analyze the ultra-low frequency oscillation of power system with large-
scale wind power, it is necessary to establish a motion equation model similar with synchronous machine.

3. Modelling of DFIG-based WT

3.1. Control Schemes of DFIG-based WT

In this paper, the GE DFIG-based WT is taken as an example [3]. The control system of a DFIG-based WT mainly includes the turbine control and the converter control as shown in Figure 2. The turbine control is constituted of the speed control and the pitch control. When there is no primary control, speed control makes sure that maximal wind energy is captured and pitch control limit the captured power ensuring the operation safety. The input of the converter control, i.e., the electromagnetic torque reference, is delivered from the turbine control. The rotor-side converter control system determines the electromagnetic torque and the reactive power of DFIG-based WT. The electromagnetic torque reference of conventional DFIG-based WT usually comes from the speed control.

The PFC of DFIG-based WT takes the frequency 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.

3.2. Small-signal modelling of DFIG-based WT

The dynamic characteristics of an equipment can be represented by the phase motion of the internal voltage. Hence, the internal voltage phase is taken as the output of the motion equation model. The internal voltage of DFIG-based WT is defined as equation [10].

\[
E = j\omega L_m I_r
\]  

(1)

The DFIG-based WT system is a nonlinear system. 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) A wind speed is set to be constant.
2) The stator transients and stator resistance are neglected.
3) Since the issue analysed 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, and voltage magnitude variation is also ignored.

Based on the assumptions as mentioned above, a linearized model of DFIG-based WT with primary control is obtained as shown in Figure 3. In addition to linearizing the control components and the internal voltage, the wind turbine component is linearized in Figure 3. The output power of wind turbine is a complex function of the wind speed, rotor speed, and pitch angle. The relationship after linearization is

$$\Delta P_m = k_c \Delta \omega + k_p \Delta \beta$$

In the control system of WTs, in order to track the phase of power system, the typical bandwidth of the PLL is relatively high. This fast dynamic is negligible, so the PLL output phase can be considered to be equal terminal voltage phase in the electromechanical time-scale. According to this, the model in Figure 3 can be further simplified.
To better describe the internal voltage phase dynamics, the active power should be only input and others need to be omitted. The active power of DFIG-based WT can be expressed by defined internal voltage and terminal voltage as shown in equation (3).

\[
P_e = EV_s \sin(\theta - \theta_s) / \omega \]

After linearization and ignoring the variation of voltage amplitude, the variation of terminal voltage phase can thus be derived.

\[
\Delta \theta_s = \Delta \theta - K_{sp} \Delta P_e
\]

where

\[
K_{sp} = E_d V_\theta \sin(\theta_s - \theta_\theta) / \omega \]

After simplification based on the above conditions, the electrical control system block diagram can be transformed into Figure 4. Through further arrangement of the model in Figure 4, a motion equation model of DFIG-based WT with primary frequency model can be obtained.

![Figure 5. Motion equation model of DFIG-based WT with primary frequency model](image)

As shown in Figure 5, this model includes an equivalent inertia \( M_{eq}(s) \), an equivalent damping \( D_{eq}(s) \) and a transfer function \( G_{pp}(s) \). Unlike the synchronous machine, the inertia and damping of DFIG-based WTs are not constant, but a complex function related to the control parameters and operation points. The transfer function \( G_{pp}(s) \) is similar with the governor of the synchronous machine. The expressions of these transfer functions are as follows:

\[
M_{eq}(s) = \frac{1}{\left(1 - K_{sp} \frac{\omega_0}{R_s} \right) \frac{k_p s + k_p}{s} \frac{1}{1 + s T_p} \left( k_{pm} + k_{pm} \right) \frac{1}{1 + s T_f}}
\]

\[
D_{eq}(s) = \frac{1}{K_{sp} \frac{(1 + s T_f)}{K_{sp} K_f s}}
\]

\[
G_{pp}(s) = \frac{K_{sp} \frac{1}{R_s} \frac{k_p s + k_p}{s} \frac{1}{1 + s T_p}}{1 - K_{sp} \frac{\omega_0}{R_s}}
\]

4. Impact Analysis of PFC of WTs on Ultra-Low Frequency Oscillation

In the following part, an extended three-machine nine-node system is taken as an example to illustrate the impact of wind power PFC on ultra-low frequency oscillation. In order to study ultra-low frequency oscillation, three synchronous machines in the system are all hydraulic turbines, and a wind farm of 100MW installed capacity is added connected to load 3 by short lines. The governor model and prime mover of hydraulic turbine is shown in Figure 7.
4.1. Analysis of impact mechanism of PFC on ultra-low frequency oscillation
Thus, we can get the open-loop transfer function of the system

\[ G_{ol}(s) = \frac{M_{eq}(s)}{M_{eq}(s)D_{eq}(s)s + 1} \]  

(8)

By studying the open-loop transfer function, the impact of PFC of DFIG-based WT on ultra-low frequency oscillation can be judged and evaluated. Based on the control theory of linear systems [21], the zero-crossing point of the amplitude frequency curve in Bode diagram corresponds to the oscillation frequency of the ultra-low frequency oscillation, and phase margin represents the damping of this oscillation. In order to ensure the stability, the phase margin should be greater than 0. If the frequency of the zero-crossing point of the amplitude frequency curve is smaller, the gain of the frequency open-loop transfer function of the system is smaller, which means the total inertia of the system is larger, so the frequency of the ultra-low frequency oscillation is lower. As for the phase margin, the smaller it is, the weaker the oscillation damping of the system is, which means the system is more unstable.

4.2. Impact law of PFC on ultra-low frequency oscillation

\[
G_{ol}(s) = \sum_{i=1}^{3} G_{govi}(s)G_{mri}(s) \left[ T_{J1} + T_{J2} + T_{J3} + G_{mr}(s) \right] s
\]  

(9)

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4.2. Impact law of PFC on ultra-low frequency oscillation

Figure 9. The Bode diagram of open-loop function under different PFC parameters

[Figure 9: Bode diagram showing the impact of PFC parameters on frequency and phase characteristics.]

Figure 10. The simulation results under different PFC parameters

[Figure 10: Simulation results illustrating the impact of PFC parameters on frequency deviation.]
The Bode diagram of open-loop transfer function with different PFC parameters is given in Figure 9 and Figure 10 shows the simulation results under a load disturbance at t=5s. Compared with the case without WT’s PFC, the zero-crossing points become larger and the phase margin also become larger when there is PFC. It’s can be easily concluded that the larger gain parameter 1/R of PFC is, the bigger zero-crossing point and phase margin are. It means with PFC, the frequency of ultra-low frequency oscillation becomes higher and the damping of ultra-low frequency oscillation turns from negative to positive. It can be proved by the simulation results shown in Figure 10. It can be seen that as the parameter 1/R increases, the oscillation after disturbance changes from divergence to convergence.

5. Conclusion

Taking DFIG-based WT as an example, this paper reveals the impact mechanism of PFC on ultra-low frequency oscillation of power system. In order to study the impact of PFC on ultra-low frequency oscillation, the motion equation model of DFIG-based WTs is proposed. Based on this, the analysis model of the power system with WTs is developed. Thus, the impact mechanism of PFC on ultra-low frequency oscillation is explained, and the impact law of PFC of DFIG-based WTs on ultra-low frequency oscillation of power system is analyzed. It can be obtained that with the PFC the ultra-low frequency oscillation is suppressed in the extended three-machine nine-node system, and the simulation results verify the conclusion.

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