Electrical Power and Energy Systems 61 (2014) 279–287

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Damping control strategies of inter-area low-frequency oscillation for DFIG-based wind farms integrated into a power system

Li Hui [a,*], Liu Shengquan [a], Ji Haiting [a], Yang Dong [a], Yang Chao [a], Chen Hongwen [b], Zhao Bin [a], Hu Yaogang [a], Chen Zhe [c]

[a] State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 400044, China
[b] State Grid Zhu Zhou Power Supply Company, Hunan 412000, China
[c] Department of Energy Technology, Aalborg University, Aalborg East DK-9220, Denmark

ARTICLE INFO

Article history:
Received 5 September 2013
Received in revised form 14 February 2014
Accepted 7 March 2014
Available online 19 April 2014

Keywords:
Wind power system
Doubly fed induction generator (DFIG)
Inter-area low-frequency oscillation
Shaft torsional oscillation
Additional damping strategy
Fuzzy logic control

ABSTRACT

This study investigates the inter-area low-frequency damping control strategies of a doubly fed induction generator (DFIG)-based wind farm through oscillation transient energy function (OTEF) analysis. Based on the OTEF descent expressions, the feasibility of damping the inter-area low-frequency oscillation is theoretically analyzed through the active/reactive power control of grid-connected wind farms. Additional damping control strategies with the active/reactive power loop of the DFIG-based wind farm are presented using the feedback signal of the transmission line active power flow based on the power system stabilizer (PSS) control method. Transient simulation on different damping gain coefficients are conducted for justification. Following the OTEF mechanism analysis, an additional fuzzy damping control strategy with the active/reactive power loop is proposed by identifying the oscillation phase and the severity to prevent different damping gain coefficients from affecting the presented PSS damping control method. Transient and dynamic simulation results and comparisons showed that both additional control strategies with the active and reactive power loops of the DFIG-based wind farm can damp the inter-area low-frequency oscillation of the integrated power system. The additional damping control strategy with the reactive power loop can damp the transmission line active power oscillation better than that with the active power loop as well as prevent an increase in the torsional oscillation of the wind turbine shaft. The proposed additional fuzzy control strategy with the active/reactive power loop has better damping performance than the presented PSS control, especially for damping the inter-area low-frequency oscillation.

Introduction

Wind energy is among the fastest-growing renewable energy technologies in the world. However, this kind of energy may threaten the stability of integrated power systems because of its large variable penetration percentage. Given the necessity of long-distance transmission lines and the remoteness of wind farms from electric power consumption centers, several operations of the power system are faced with high stability risks, particularly in inter-area low-frequency oscillation [1–4]. A low-frequency oscillation in a power system that is integrated with wind farms may greatly limit the power transferring capability of and cause additional shaft torsional oscillation to the wind turbine generator system (WTGS), effects that may harm the operations of wind farms.

Several studies have proposed the use of the power system stabilizer (PSS) for damping low-frequency inter-area oscillation [5–8]. However, these studies mostly focused on traditional synchronous generators. The damping capability of inter-area low-frequency oscillation in wind farms that are integrated into power systems must be examined because the spread of these farms are changing the structure of the power system. Doubly fed induction generator (DFIG) wind turbines are extensively used in wind farms because of their variable speed constant frequency performance and their capability to decouple active and reactive powers by using a partially rated power converter on the rotor side [9–15]. The contribution of DFIG in damping inter-area oscillation has been examined in several studies [13,16–19]. In [16,17], the authors designed a PSS damping control strategy with the active power loop and examined how the system-dominant eigenvalue distribution is affected by the PSS gain as well as by the location and operation of the wind farm. The simulation results in [17] show that the additional PSS control consistently contributes to

* Corresponding author.
E-mail address: cqulh@163.com (H. Li).

http://dx.doi.org/10.1016/j.ijepes.2014.03.009
0142-0615/

damping oscillation over full operation slip without degrading the control ability of output voltage. In [18,19], the authors designed a wide-area damping controller for damping low-frequency transmission power oscillation. However, these studies only considered the transmission power oscillation damping effect and ignored the possibility of these control strategies to cause shaft torsional oscillation or to destabilize the operations of WTGS. In addition, the presented damping control strategies are primarily based on the active power loop of DFIG, and the designed controller parameters are dependent on the try and trial method or the experience. Furthermore, these studies have also largely ignored the damping mechanism of the low-frequency oscillation. Therefore, the damping mechanisms of low-frequency oscillation for different control strategies must be investigated, and a suitable additional control strategy of DFIG-based wind farms that can effectively damp inter-area low-frequency oscillation in the power system and reduce shaft torsional oscillation in the WTGS must be proposed. Given the robust characteristics and adaptive parameters of the fuzzy logic control strategy [20–23], an additional damping strategy with a fuzzy logic control of DFIG-based wind farms must be investigated further through the analysis of damping mechanisms.

This paper analyzes the damping mechanisms and presents a suitable additional damping control strategy of a DFIG-based wind farm that can depress the inter-area low-frequency oscillation of the integrated power system. The feasibility of damping the inter-area low-frequency oscillation is theoretically analyzed through the active/reactive power control of the grid-connected wind farms by deriving the descent expressions of oscillation transient energy function (OTEF). To validate the damping mechanism, the additional damping control strategies with active/reactive power loop of a DFIG-based wind farm are presented using the feedback signal of the transmission power flow following the PSS method. The control results with different gain coefficients are simulated for justification. To prevent different gain parameters from affecting the presented PSS control, an additional fuzzy damping control strategy with the active/reactive power loop is proposed by identifying the oscillation phase and the severity. The additional damping control strategies in an IEEE two-area, four-machine power system integrated with a DFIG-based wind farm are simulated and compared.

The contribution of this paper is to investigate the inter-area low-frequency oscillation damping control strategies of a DFIG-based wind farm integrated into the power system. Section 2 analyzes the damping mechanisms based on the OTEF method, Section 3 presents and simulates the additional PSS damping control strategies with active/reactive power loop, Section 4 proposes a fuzzy damping control strategy as well as defines the fuzzy membership function and rule bases, and Section 5 concludes the study.

Mechanism analysis of damping inter-area power oscillation

Inter-area oscillation analysis with transient energy function

To analyze the damping inter-area power oscillation mechanisms, a two-area power system integrated with a wind farm that is installed in area A is used as an example to explain the power system OTEF concept. As shown in Fig. 1, the system dynamic motion equations between the centers of inertia (COI) of areas A and B can be described as follows [24]:

$$\frac{d\omega_{AB}}{dt} = \frac{1}{M_A}(P_{A0} + P_w - P_A) - \frac{1}{M_B}(P_{B0} + P_B) \tag{1}$$

$$\frac{d\delta_{AB}}{dt} = \omega_{AB} \tag{2}$$

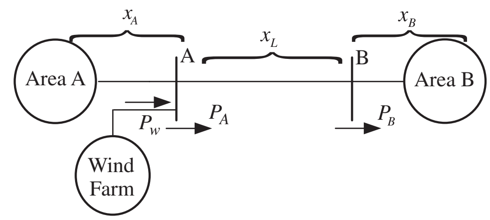

Fig. 1. Two-area power system integrated with a wind farm.

where δ_{AB} and ω_{AB} denote the difference in swing angles and angle speeds of the COIs of areas A and B respectively, P_{A0} and P_{B0} denote the total power generation and consumption in areas A and B respectively, P_A and P_B denote the transmission flow in bus A and bus B respectively, M_A and M_B denote the system inertia constants of the COIs of areas A and B respectively, and P_w denotes the output active power of the grid-connected wind farm.

Multiplying both sides of Eq. (1) with ω_{AB} and integrating the results leads to the following equation:

$$\frac{1}{2}\omega_{AB}^2 - \frac{1}{2}\omega_{AB0}^2 + \int_{\delta_{AB0}}^{\delta_{AB}} -\left[\frac{1}{M_A}(P_{A0} + P_w - P_A) - \frac{1}{M_B}(P_{B0} + P_B)\right] d\delta_{AB} = \text{constant} \tag{3}$$

where ω_{AB0} and δ_{AB0} denote the values of ω_{AB} and δ_{AB} at the equilibrium point respectively. As shown in Eq. (3), the total transient power stored in the machines and the network will remain constant when there is no damping in the power system. When the equilibrium point angle speed ω_{AB0} is zero, the oscillation kinetic energy (OKE) and oscillation potential energy (OPE) of the power system can be computed as follows:

$$V_{KE} = \frac{1}{2}\omega_{AB}^2 \tag{4}$$

$$V_{PE} = \int_{\delta_{AB0}}^{\delta_{AB}} -\left[\frac{1}{M_A}(P_{A0} + P_w - P_A) - \frac{1}{M_B}(P_{B0} + P_B)\right] d\delta_{AB} \tag{5}$$

where V_{KE} and V_{PE} denote OKE and OPE respectively.

Fig. 2 shows the oscillation curves for swinging δ_{AB} and swinging ω_{AB} in a zero damping power system.

As shown in Fig. 2, one oscillation cycle can be divided into four stages based on the state of ω_{AB}.

Stage I: Backward acceleration stage ($d\omega_{AB} < 0$ and $\omega_{AB} < 0$, $[t_a, t_b]$). In this stage, ω_{AB} gradually increases from zero to the minimum value ω_{ABmin}, OPE gradually reduces to become the minimum value, and OKE gradually increases to become the maximum value $1/2\omega^2_{ABmin}$.

Stage II: Backward deceleration stage ($d\omega_{AB} > 0$ and $\omega_{AB} < 0$, $[t_b, t_c]$). In this stage, ω_{AB} gradually reduces from the minimum value ω_{ABmin} to zero, OKE gradually reduces to become the

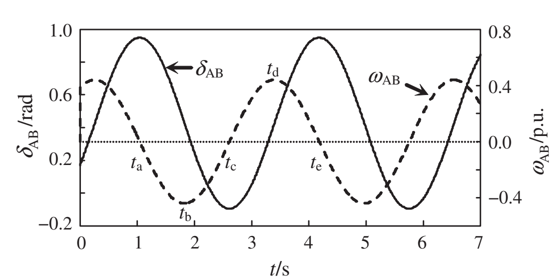

Fig. 2. Oscillation characteristics of δ_{AB} and ω_{AB} in a zero damping power system.