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An investigation on interarea mode oscillations of interconnected power systems with integrated wind farms

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ABSTRACT

The ever-increasing penetration of wind power integration into a power system can produce significant impacts on the operation of an interconnected power system. As the major energy conversion technology for large wind turbines, the doubly fed induction generator (DFIG) will play an important role in future power systems. Hence, the impacts of the DFIG on the low-frequency oscillations of interconnected power systems have become an important issue with extensive concerns. This paper examines the impacts of several factors, including the DFIG transmission distance, tie-line power of the interconnected system, DFIG capacity, with/without a power system stabilizer (PSS), on the low frequency oscillation characteristic of an interconnected power system using both eigenvalue analysis and dynamic simulations. To investigate the effects of these factors on the interarea oscillation mode, case studies are carried out on two two-area interconnected power systems, and some conclusions are obtained.

Introduction

The interconnections of province-level electric power grids have been carried out in China since 2001 [1], as manifested by several interconnection projects such as Northeast China to North China, Chuanyu to Central China, Fujian to East China. Meanwhile, wind energy has been paid more and more attention in many parts over the world [2,3] because of the advantages in relieving energy crisis, protecting environment and promoting sustainable development. With the development of wind energy technology, it is expected that more and more large-scale wind farms will be connected to power systems.

In recent years, the doubly-fed induction generator (DFIG) has become the dominant type among the new installed wind turbines due to its capability of controlling reactive power, high energy efficiency, and the fact that the converter rating of appropriately 20–30% of the total machine power is needed. With the increasing penetration level of wind power generation, the impacts of wind power on actual power systems have drawn much attention around the globe [4–7]. It is well known that the power network interconnection is useful for optimizing the distribution of resources and improving network reliability, but also bringing some new challenges to power system operation such as low frequency oscillation. Thus, it is necessary to systematically examine how the DFIG penetration affects an actual interconnected large-scale power system, especially on low frequency oscillation characteristic [7–10].

An interconnected power system formed by an N-machine independent power system and an M-machine one, has $M + N - 1$ electromechanical oscillation modes, one more than the sum of the two independent power systems. Typically, low frequency oscillations are classified as local mode oscillations and interarea mode oscillations [11]. The former is caused by interactions among a few generators close to each other with frequencies in the range of 0.5–2.0 Hz, while the latter by interactions among large groups of generators with frequencies in the range of 0.1–1.0 Hz.

Recently, some research work has been done regarding the interarea mode oscillation of an interconnected power system with wind power integrated. The issues of large wind farm integration and its potential impact on power system damping characteristic were first addressed in 2003 by Slootweg et al. [12]; since then much research work has been carried out by modal analysis or time-domain simulations. In [13,14], the impacts of wind power

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on oscillations and damping were investigated by gradually replacing the power generated by synchronous generators with wind power respectively in New Zealand and Nordic power system.

Up to now, the impacts of some important factors, such as the DFIG transmission distance, tie-line power of the interconnected system, DFIG capacity, with/without a power system stabilizer (PSS), on the low frequency oscillation characteristic of an interconnected power system have not yet been systematically investigated, and this is the focus of this paper. Based on the comprehensive model of DFIG, the damping performances of a two-area interconnected system with wind power integration are quantitatively analyzed. The impacts of the above mentioned factors on the interarea mode oscillation are examined for a 2-area 4-unit power system and a 2-area 8-unit 24-bus one by eigenvalue analysis and dynamic simulations. The results of this study are expected to provide some reference for the plan, design, and operation of wind power integration into an interconnected power system, and for the comprehensive understanding of the interarea mode oscillation in this kind of power systems.

Low frequency oscillation in a simple interconnected power system

Relative to the inertia center of a power system, there are always two groups, i.e. one with accelerated generators and the other with decelerated generators, when an oscillation occurs in an interconnected power system. These demonstrates the relative swing of the two groups, and the coherent characteristic in the same group. An interconnected power system can be simplified into two equivalent machines [11] whose speed deviation ($\Delta\omega_1$, $\Delta\omega_2$) and power angle deviation ($\Delta\delta_1$, $\Delta\delta_2$) have the characteristic of reversed-phase sinusoidal oscillators with the same frequency, as shown in Fig. 1. The tie line power is transmitted from area 1 to area 2, i.e., areas 1 and 2 are respectively the sending end and the receiving end.

To simplify the analysis, the second-order classical model for generators and the constant impedance models for loads are employed. The rotor motion equations of the 2-generator interconnected power system can be expressed as

$$\begin{cases} \Delta\dot{\delta}_1 = \Delta\omega_1 \\ \Delta\dot{\delta}_2 = \Delta\omega_2 \\ \Delta\dot{\omega}_1 = (\Delta P_{1m} - \Delta P_{1e} - D_1\Delta\omega_1)/M_1 \\ \Delta\dot{\omega}_2 = (\Delta P_{2m} - \Delta P_{2e} - D_2\Delta\omega_2)/M_2 \end{cases} \quad (1)$$

where $\Delta\omega_1$ and $\Delta\omega_2$ are the speed deviations of G_1 and G_2, respectively; $\Delta\delta_1$ and $\Delta\delta_2$ are the two generators' power angle deviations, respectively; M_1 and M_2 are the two generators' inertia time constants, respectively; D_1 and D_2 are the two generators' damping torque coefficients; ΔP_{1m} and ΔP_{2m} are the two generators' mechanical power deviations; ΔP_{1e} and ΔP_{2e} are the electromagnetic power deviations.

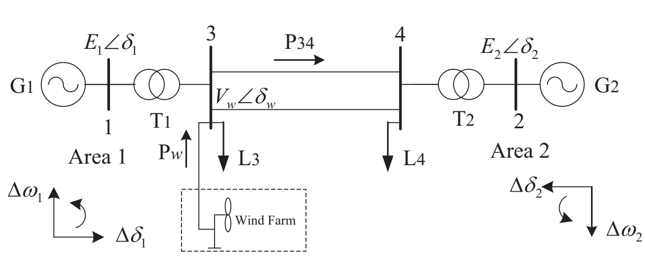

Fig. 1. A two-generator interconnected power system.

Suppose that $\Delta P_{1m} = \Delta P_{2m} = 0$, from Eq. (1) the Heffron-Phillips model with the state matrix form can be obtained as follows.

$$\begin{bmatrix} \Delta\dot{\delta}_1 \\ \Delta\dot{\delta}_2 \\ \Delta\dot{\omega}_1 \\ \Delta\dot{\omega}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{K_{11}}{M_1} & -\frac{K_{12}}{M_1} & -\frac{D_1}{M_1} & 0 \\ -\frac{K_{21}}{M_2} & -\frac{K_{22}}{M_2} & 0 & -\frac{D_2}{M_2} \end{bmatrix} \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \Delta\omega_1 \\ \Delta\omega_2 \end{bmatrix} = \boldsymbol{A_S} \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \Delta\omega_1 \\ \Delta\omega_2 \end{bmatrix} \quad (2)$$

where $K_{ij} = \partial P_{ei}/\partial\delta_j$ is generators' synchronizing torque coefficients at the operating point; $\boldsymbol{A_S}$ is the state matrix.

The electromagnetic power of G_1 and G_2 can be calculated as

$$\begin{cases} P_{1e} = E_1^2/|Z_{11}|\sin\alpha_{11} + E_1E_2/|Z_{12}|\sin(\delta_{12} - \alpha_{12}) \\ P_{2e} = E_2^2/|Z_{22}|\sin\alpha_{22} + E_1E_2/|Z_{12}|\sin(\delta_{12} - \alpha_{12}) \end{cases} \quad (3)$$

where Z_{ii} is the input impedances; Z_{ij} is the transfer impedance, and $Z_{ii} = |Z_{ii}|\angle\varphi_{ii}$, $Z_{ij} = |Z_{ij}|\angle\varphi_{ij}$; the impedance angles can be expressed as $\varphi_{ii} = 90^\circ - \alpha_{ii}$, $\varphi_{ij} = 90^\circ - \alpha_{ij}$.

δ_{120} is used to represent the relative angle between G_1 and G_2 at a given operating point. The synchronizing torque coefficients can be derived from Eq. (3) as

$$\begin{cases} K_{11} = -K_{12} = E_1E_2/|Z_{12}|\cos(\delta_{120} - \alpha_{12}) \\ K_{22} = -K_{21} = E_1E_2/|Z_{12}|\cos(\delta_{120} - \alpha_{12}) \end{cases} \quad (4)$$

Based on matrix transformations and the Schur theorem, the characteristic equation of the state matrix $|\boldsymbol{A_S} - \lambda\boldsymbol{I}| = 0$ can be expressed as

$$\lambda^4 + \left(\frac{D_1}{M_1} + \frac{D_2}{M_2}\right)\lambda^3 + \left(\frac{K_{11}}{M_1} + \frac{K_{22}}{M_2} + \frac{D_1}{M_1}\frac{D_2}{M_2}\right)\lambda^2 + \frac{1}{M_1M_2}(D_1K_{22} + D_2K_{11})\lambda = 0 \quad (5)$$

If $D_1/M_1 = D_2/M_2 = \gamma$, i.e. the mechanical damping coefficients are homogeneous, then Eq. (5) can be simplified as

$$\lambda(\lambda + \gamma)\left(\lambda^2 + \gamma\lambda + \frac{K_{11}}{M_1} + \frac{K_{22}}{M_2}\right) = 0 \quad (6)$$

The eigenvalues of Eq. (6) are: $\lambda_1 = 0$, $\lambda_2 = -\gamma = -D_1/M_1$, $\lambda_3 = \sigma \pm j\omega = -D_1/2M_1 \pm j\sqrt{-(D_1/M_1)^2 + 4(K_{11}/M_1 + K_{22}/M_2)}/2$.

K_{11}, K_{22}, D_1 and D_2 are all positive under normal operating conditions. It can be proved that Eq. (6) satisfies the Routh stability criterion, and the real parts of three nonzero eigenvalues are negative. λ_3 represents the electro-mechanical modes of this two-generator power system. If the system is negative damping or zero damping, i.e. $D \leqslant 0$ and $-D/M \geqslant 0$, then the real parts of eigenvalues are situated on or at the right of the imaginary axis, and this demonstrates that the system is small signal unstable.

Modeling of DFIG

Drive train

The drive train is usually represented by a two-mass model [3] and its dynamics can be expressed by the following differential equations.

$$\begin{cases} d\omega_r/dt = (T_{sh} - T_e - D_t\omega_r)/2H_g \\ d\theta_t/dt = \omega_b(\omega_t - \omega_r) \\ d\omega_t/dt = (T_m - T_{sh})/2H_t \end{cases} \quad (7)$$

where H_t and H_g are the inertia constants of the turbine and the generator, respectively; ω_r and ω_t are the generator and wind turbine speeds, respectively; ω_b is the reference speed; θ_t is the shaft twist angle; D_t is the damping coefficient of wind turbine (WT).