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Model order reduction based dynamic equivalence of a wind farm

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ABSTRACT

This paper presents dynamic equivalence of a wind farm based on the model order reduction (MOR) methods. A doubly-fed induction generator (DFIG) with complete mechanical, electrical and control components is the basis for model development. For the purpose of wind fluctuation simulation, the dynamic model of DFIG can be seen as a linear input–output system with the incoming wind speed as the input and the generated active power as the output. Linear model reduction techniques, dominant pole based modal analysis (DPMA) and balanced truncation (BT), combined with classical aggregation skills are applied to obtain a new low-order system representing a wind farm. Simulations and comparisons are carried out in the test system to validate the ability of the reduced order model in matching the active power generated by the detailed wind farm model.

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Introduction

Wind power has been identified as one of the promising successors of conventional power generation technologies. Compared with fossil fuels, wind energy is renewable, plentiful, widely distributed and environmentally friendly. By 2011, the total nameplate capacity of wind energy had surpassed 238 GW, which occupied more than 2.5 percent of worldwide energy usage. It is estimated that wind power penetration will rise to 8 percent in 2018 [1].

Wind farms are typically assemblages of tens to hundreds of small-sized wind turbine generators (WTGs). Adding all units in the farm to a detailed model would lead to the problem of solving very high-order differential algebraic equations (DAEs), which results in enormous computation complexity. Meanwhile, the complete model of single DFIG contains dynamics of different time scales. Numerical integration of such a stiff system is difficult unless the step size is taken to be extremely small. Thus, a reduced order but accurate enough equivalent WF model is required for power system analysis.

So far, common ways to establish an equivalent wind farm model can be divided into two categories: coherency based aggregation and model order reduction originated from the control theory. The coherency based method, which is probably most commonly used for synchronous power systems, consists of two main steps: (1) identifying coherent groups of WTGs, and (2) aggregating each coherent group into a single equivalent WTG. Three different types of aggregation were presented in previous literature: single machine equivalence [2–4], multi-machine equivalence [5] and compound equivalence [6]. Most methods discussed above are heuristic (based on prior-experience) or semi-heuristic and lack strict mathematical justification. Therefore, it is necessary to apply model order reduction methods originated from system theory to wind farm dynamic equivalence [7].

The idea of MOR is to replace a given mathematical model of a system by a model that is much smaller than the original ones, yet still accurately describes the input–output behaviors of the system. The reduced order model is effective when the following properties are satisfied: (1) the approximation error is small, and there exists a global error bound; (2) system properties (like stability or passivity) are preserved; (3) the procedure is computationally stable and efficient [8].

Depending on the properties of the original system that are retained in the reduced model, there are different model reduction methodologies. Generally, model reduction techniques are based on:

(1) Identifying and preserving certain modes of interest directly. (modal truncation and selective modal analysis).
(2) Singular value decomposition (SVD) which preserves the observability and controllability of the system. (balanced truncation and Hankel norm approximation).
(3) Moment matching which approximates the moments of the transfer functions of the original system (Krylov method).
(4) Singular perturbation analysis, which assumes that the original system can be divided into fast and slow dynamic subsystems.

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Some researchers in this field have introduced MOR methods to wind farm modeling. In [9], singular perturbation analysis was applied to fixed speed WTGs and a reduced order model that neglects the fast dynamics was obtained. In [10], a simplified first order representation of an individual WTG in a wind farm was presented and BT method was introduced to reduce the order of the whole wind farm. Hector utilized selective modal analysis to the simplified DFIG [11] and presented some preliminary results for its application to wind farm modeling [12].

In this paper, MOR methods for a detailed wind farm are presented and compared. The methods of dominant pole based modal analysis and balanced truncation are selected due to their simplicity. The proposed methods can be applied to dynamic simulation of the power system with wind farms to reduce computation burden. Meanwhile, the reduced models have the potentials in the wind farm controller design for inertial and primary frequency response [13]. The rest of the paper is organized as follows. In Section "WTG dynamic modeling", the dynamic model of a DFIG, containing a two-mass shaft model with both rotor side and grid side converters, is presented. In Section "Linearized model of a wind farm", the linearized input–output model of a wind farm is developed. In Section "Model order reduction of linear system", the principle of DPMA and BT algorithm is introduced. Validation of the proposed methods and conclusion are presented in Sections "Numerical results" and "Conclusion" respectively.

WTG dynamic modeling

To emphasize the generality of the formulation, a detailed model of DFIG is considered. It is simplified using the following assumptions:

- The wind speed is within its technical limits, which means the pitch angle controller can be omitted.
- The nonlinear maximum power point tracking (MPPT) curve is represented by a third-order polynomial function [14].
- The transient process of the stator is neglected, as it is much faster than those of other components.

In this way, the entire model can be divided into two parts: the mechanical part and the electrical part.

The mechanical part is composed of a wind turbine and a two-mass drive chain system. The wind turbine converts the wind energy into kinetic energy. The drive chain system can be represented by either a two-mass or a lumped-mass model. It is believed that the lump-mass model does not exhibit any low-frequency torsional oscillations that exist in the practical WTG and in the two-mass shaft model [15]. Therefore, the two-mass shaft model is considered for the study.

The electrical part includes a generator and two power converters. A third order generator model is adopted, which is similar with that of traditional induction generator. Both of the rotor side converter (RSC) and the grid side converter (GSC) are controlled via two cascaded control loops. In general, the RSC controller is designed to extract maximum power from the wind and to regulate the reactive power. The GSC controller regulates the dc-link voltage and the reactive power exchanged between the GSC and the grid.

The complete DAEs of a DFIG contain 14 differential equations and 16 algebraic equations. The differential equations are shown as follows:

$$\dot{E}'_q = -\frac{1}{T'_0}\left[E'_q + (X_s - X'_s)I_{ds}\right] + \omega_s\left(\frac{X_m}{X_r}V_{dr} - (1-\omega_g)E'_d\right) \tag{1}$$

$$\dot{E}'_d = -\frac{1}{T'_0}\left[E'_d - (X_s - X'_s)I_{qs}\right] - \omega_s\left(\frac{X_m}{X_r}V_{qr} - (1-\omega_g)E'_q\right) \tag{2}$$

$$2H_g\dot{\omega}_g = K_{tg}\theta_S/T_{base} - T_e - D_{tg}(\omega_{base}\omega_g - \omega_t)/T_{base} \tag{3}$$

$$\dot{x}_1 = K_{I1}(P_{ref} - P_{gen}) \tag{4}$$

$$\dot{x}_2 = K_{I2}(K_{P1}(P_{ref} - P_{gen}) + x_1 - I_{qr}) \tag{5}$$

$$\dot{x}_3 = K_{I3}(Q_{ref} - Q_{gen}) \tag{6}$$

$$\dot{x}_4 = K_{I4}(K_{P3}(Q_{ref} - Q_{gen}) + x_3 - I_{dr}) \tag{7}$$

$$\dot{V}_{dc} = [V_{dg}I_{dg} + V_{qg}I_{qg} - (V_{dr}I_{dr} + V_{qr}I_{qr})]/C_dV_{dc} \tag{8}$$

$$\dot{x}_5 = K_{I5}(V_{dc\_ref} - V_{dc}) \tag{9}$$

$$\dot{x}_6 = K_{I6}(K_{P5}(V_{dc\_ref} - V_{dc}) + x_5 - I_{dg}) \tag{10}$$

$$\dot{x}_7 = K_{I7}(Q_{grid\_ref} - Q_{grid}) \tag{11}$$

$$\dot{x}_8 = K_{I8}[K_{P7}(Q_{grid\_ref} - Q_{grid}) + x_7 - I_{qg}] \tag{12}$$

$$J_t\dot{\omega}_t = T_w - K_{tg}\theta_S - D_{tg}(\omega_t - \omega_{base}\omega_g) \tag{13}$$

$$\dot{\theta}_S = \omega_t - \omega_{base}\omega_g \tag{14}$$

where the subscripts s, r, g, D, d and q indicate the stator, the rotor side, the grid side, the terminal bus, the d-axis, and the q-axis of the DFIG respectively. E'_q and E'_d are q-axis and d-axis transient rotor voltages, T'_0 is the transient open-circuit time constant. $X'_s = X_s - X_m^2/X_r$ is the transient reactance. V_{Dx} and V_{Dy} denotes the real and imaginary part of the stator voltage. V_{dc} is the voltage of dc-link. C_d is the capacitance. For the two-mass shaft model, ω_g and ω_t are the generator speed in per unit system and turbine speed in physical unit system respectively. $\omega_{base} = 2\pi f/pk_{gear}$ is the base speed. T_e is the electrical torque, T_w is the torque extracted from the wind. H_g is the generator inertia and J_t is the moment of inertia of wind turbine. K_{tg} is the shaft stiffness, D_{tg} is the shaft damping coefficient and θ_s is the twist angle of shaft. The state variables x_1 to x_8 are related to RSC and GSC controllers. K_{P1}, K_{I1} to K_{P8}, K_{I8} are the controllers' PI parameters. P_{ref} is obtained for the MPPT curve, which is defined by

$$P_{ref} = C\omega_g^3 \tag{15}$$

In this study, the coefficient C equals to 0.4552.

The mechanical torque applied to the wind turbine and the electrical torque of the generator are defined respectively by

$$T_w = 0.5\rho\pi R^2 C_p(\lambda,\theta)V_w^3/\omega_t \tag{16}$$

$$T_e = E'_qI_{qs} + E'_dI_{ds} \tag{17}$$

The computation of T_w depends on the power coefficient C_p, air density ρ, turbine radius R, and wind velocity V_w. C_p is a function of the turbine blade tip speed ratio λ and the blade pitch angle θ. As the most concerned output, the generated active power of the DFIG can be stated as:

$$P_{gen} = E'_qI_{qs} + E'_dI_{ds} - \left(I_{ds}^2 + I_{qs}^2\right)R_s + V_{dg}I_{dg} + V_{qg}I_{qg} - \left(I_{dg}^2 + I_{qg}^2\right)R_g \tag{18}$$

More details of the DFIG model can be found in Appendix A.

Linearized model of a wind farm

For system impact studies, an individual WTG will generally not exert a significant influence on the dynamic behavior of power

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