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Comparison analysis on damping mechanisms of power systems with induction generator based wind power generation

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ABSTRACT

The rotor structure varies with different types of wind power induction generator (WPIG), which leads to their different dynamic behaviors during power system disturbances. This paper proposes a generic implementation framework of explicit damping torque analysis to investigate the damping mechanisms of power system integrated with induction generator based wind power generation, so that the essential difference and inner connection between two main types of WPIG (i.e., DFIG and FSIG) in damping power system oscillation can be revealed. The linearized models which can represent DFIG and FSIG as well as three transitional wound rotor generators are established to facilitate the analytical comparison analysis. Phillips-Heffron system linearized model is employed to derive an explicit expression of damping torque contribution from main dynamic components of WPIGs. In the paper, 16-machine 5-area NYPS-NETS example system is used for the demonstration of proposed framework and comparison analysis. Both damping effectiveness and robustness of different WPIGs are extensively examined under multiple operating status, in order to provide useful guidance to system planner for the real-time operation of induction generator based wind generation.

1. Introduction

1.1. Background and motivation

Induction generator based wind power generation has been dominating the wind market since the rise of wind power industry at the end of last century and will be continuously in a favorable position for large-scale grid connection given its lower cost and more mature technology compared with other wind generation for the foreseeable future [1]. Fixed-speed induction generator (FSIG-Type 1 Wind Gen Model) and doubly-fed induction generator (DFIG-Type 3 Wind Gen Model) are two main types of induction generator adopted for wind power generation especially considering the fact that DFIG is the most frequently-used technology to date.

The increasing penetration of wind power generation has significantly affected power system dynamics, e.g., system inertia, which has become smaller but more changeable depending on the wind penetration conditions. Moreover, due to the difference in rotor structures and excitation principles, FSIG and DFIG possess different dynamic behaviors during system disturbances and hence impact the power system dynamics differently, which has posed a big challenge for the real-time system operation and therefore deserves a careful investigation.

1.2. Literature review

The impact of the integration of FSIG and DFIG on power system oscillation stability have been extensively examined from early this century. A comprehensive study regarding the influence of FSIG on power system oscillation is presented in [2] by modal analysis, which considers multiple impact factors including length of transmission interface, load condition, wind penetration level and wind farm configuration, etc. It is concluded that in most cases FSIG introduces a negative damping to the system and additional reactive power compensation could mitigate the negative impact of FSIG on oscillation stability. This conclusion is supported by modal analysis in [3] but contradicted by [4]. Compared with FSIG, DFIG is comparatively new and has a more flexible control in active and reactive power, and thus most of research efforts are devoted to the grid connection study of DFIG in recent decade. Various case studies have been implemented to address different aspects of DFIG in affecting the oscillation stability such as integration method [4–9], inertia or other sensitivity based

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approach [10–12], reactive power/voltage control [13–17], operating condition [18], virtual inertia control [19–21], additional damping control [22–32] and external energy storage system [33,34].

It can be seen from the above review that: 1. Most of the existing research is actually case-by-case observation by using the two common 'computation' methods (modal analysis & time domain simulation), and thus the essential reason for inconsistent study results with different preconditions cannot be effectively and convincingly investigated by these two 'black box' methods. No proper theoretical method is seen so far to clearly reveal the essential damping mechanism of power system oscillation stability as affected by FSIG and DFIG; 2. Most of the published research tends to study the grid impact of FSIG and DFIG separately and there is no systematic analytical theory to compare the damping effectiveness and robustness of these two wind power induction generators (WPIGs) and dig deeper information about their essential difference and inner connection in affecting power system oscillations, which will certainly provide a better understanding of their individual damping mechanisms.

1.3. Contribution and structure of this paper

Taking account of the points above, a generic methodology to analyze the damping mechanisms of different WPIGs is proposed in this work, with the aim of giving a physical insight that how the different rotor structures and excitation systems of FSIG and DFIG affect their damping mechanisms. The major contributions of the work can be summarized as follows: 1. A generic and explicit analytical method for damping torque analysis of different WPIGs is proposed, which is based in frequency domain but capable of providing deeper understandings about damping mechanisms than modal analysis. Although the focus of this paper is on FSIG and DFIG and the comparison of their different excitation systems, the proposed method can accommodate the case of DFIG with external damping controllers and also it can be further developed to assess the full-converter decoupled generator (Type 4 Wind Gen Model), which will be addressed in the future work; 2. Two typical linearized models and explicit transfer functions of WPIGs (i.e., DFIG and FSIG) are established to facilitate the detailed investigation and comparison of damping mechanisms; 3. Unlike above-mentioned numerical comparison (case-by-case study), a purely analytical comparison of damping mechanisms between different WPIGs is implemented and their essential difference and inner connection in damping mechanisms are revealed. Some significant empirical conclusions regarding damping effectiveness and robustness of the two typical WPIGs have been rigorously proved in an analytical manner for the first time.

The rest of paper is organized as follows. In Section 2, a general implementation framework of explicit damping torque analysis of Phillips-Heffron model based multi-machine power system is presented. Hence, the closed-form solution of damping torque contribution from the main internal dynamic components of wind generators to each synchronous generator can be derived. Then in Section 3, the explicit linearized models of different WPIGs are proposed to accommodate the analytical comparison on the impact mechanisms of DFIG and FSIG, where FSIG is treated as a special case of DFIG with rotor side short-circuit (i.e., rotor voltage equal to zero). In Section 4, the proposed methodology is demonstrated in a 16-machine test system and then employed to testify the conclusions of comparison analysis from Section 3 under different wind penetration conditions. Time domain simulation is employed to prove the accuracy of the proposed methodology in frequency domain.

2. Generic implementation framework of explicit damping torque analysis of Phillips-Heffron model based multi-machine power system with WPIGs

Based on the derivation in Appendix A, the explicit Phillips-Heffron linearized model of a multi-machine power system considering the algebraic interface equations of WPIGs can be established in (1), where state variables ($\boldsymbol{\Delta\delta}$,$\boldsymbol{\Delta\omega}$,$\boldsymbol{\Delta E'_q}$ and $\boldsymbol{\Delta E_{fd}}$) and matrix elements ($\boldsymbol{\omega_0}$,$\boldsymbol{M}$,$\boldsymbol{D}$,$\boldsymbol{K}_1 \sim \boldsymbol{K}_6$,$\boldsymbol{T_{d0}}$,$\boldsymbol{K_A}$ and $\boldsymbol{T_A}$) of synchronous generators (SGs) are defined in Chapter 3.1 of [35], $\boldsymbol{\Delta s}$, $\boldsymbol{\Delta E_d}$ and $\boldsymbol{\Delta E_q}$ is the vector of variation of slip and direct/quadrant-axis electromotive force of WPIGs, and the rest elements ($\boldsymbol{K_{\omega1}}$,$\boldsymbol{K_{\omega2}}$,$\boldsymbol{K_{\omega3}}$,$\boldsymbol{K_{E'_q1}}$,$\boldsymbol{K_{E'_q2}}$,$\boldsymbol{K_{E'_q3}}$,$\boldsymbol{K_{Efd1}}$,$\boldsymbol{K_{Efd2}}$ and $\boldsymbol{K_{Efd3}}$) are calculated in Appendix A. According to (1), it can be noted that: 1. The linearized model presented in (1) is an open-loop system with $\boldsymbol{\Delta s}$, $\boldsymbol{\Delta E_d}$ and $\boldsymbol{\Delta E_q}$ as its control variables, since the internal dynamics of WPIGs is not included. Hence, (1) is also named system-side linearized model in this paper; 2. Only the state variables of induction generator ($\boldsymbol{\Delta s}$, $\boldsymbol{\Delta E_d}$ and $\boldsymbol{\Delta E_q}$) have a direct impact on the system damping and other state variables (e.g., state variables of DFIG converter controllers) affect system via $\boldsymbol{\Delta s}$, $\boldsymbol{\Delta E_d}$ and $\boldsymbol{\Delta E_q}$. For FSIG, $\boldsymbol{\Delta s}$ does not directly contribute to the system damping either since FSIG rotor is a closed circuit and thus physically separate from the grid. However, to keep a consistent form for the demonstration of WPIG, $\boldsymbol{\Delta s}$ can be retained in (1) but with $K_{\omega1} = K_{E'_q1} = K_{Efd1} = 0$.The linearized model in (1) is illustrated by Fig. 1 in frequency domain and p is the frequency domain operator.

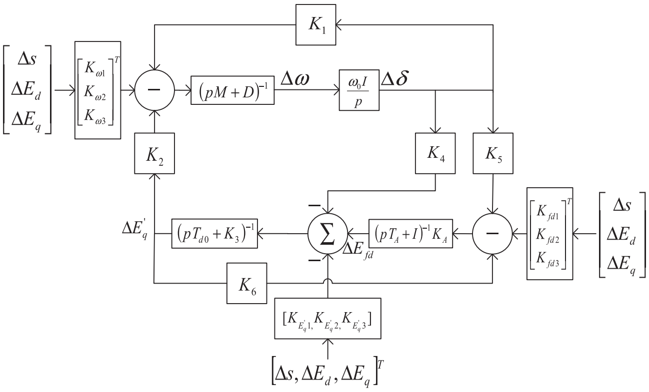

Fig. 1. System-side linearized model diagram of power system integrated with WPIGs.

$$
\begin{bmatrix}\Delta\dot{\delta}\\ \Delta\dot{\omega}\\ \Delta\dot{E}'_q\\ \Delta\dot{E}_{fd}\end{bmatrix}
=
\begin{bmatrix}
\mathbf{0} & \boldsymbol{\omega_0 I} & \mathbf{0} & \mathbf{0}\\
-\boldsymbol{M}^{-1}\boldsymbol{K}_1 & -\boldsymbol{M}^{-1}\boldsymbol{D} & -\boldsymbol{M}^{-1}\boldsymbol{K}_2 & \mathbf{0}\\
-\boldsymbol{T}_{d0}^{-1}\boldsymbol{K}_4 & \mathbf{0} & -\boldsymbol{T}_{d0}^{-1}\boldsymbol{K}_3 & \boldsymbol{T}_{d0}^{-1}\\
-\boldsymbol{T}_A^{-1}\boldsymbol{K}_A\boldsymbol{K}_5 & \mathbf{0} & -\boldsymbol{T}_A^{-1}\boldsymbol{K}_A\boldsymbol{K}_6 & -\boldsymbol{T}_A^{-1}
\end{bmatrix}
\begin{bmatrix}\boldsymbol{\Delta\delta}\\ \boldsymbol{\Delta\omega}\\ \boldsymbol{\Delta E'_q}\\ \boldsymbol{\Delta E_{fd}}\end{bmatrix}
+
\begin{bmatrix}\mathbf{0}\\ -\boldsymbol{M}^{-1}\boldsymbol{K}_{\omega1}\\ -\boldsymbol{T}_{d0}^{-1}\boldsymbol{K}_{E'_q1}\\ -\boldsymbol{T}_A^{-1}\boldsymbol{K}_A\boldsymbol{K}_{Efd1}\end{bmatrix}\boldsymbol{\Delta s}
+
\begin{bmatrix}\mathbf{0}\\ -\boldsymbol{M}^{-1}\boldsymbol{K}_{\omega2}\\ -\boldsymbol{T}_{d0}^{-1}\boldsymbol{K}_{E'_q2}\\ -\boldsymbol{T}_A^{-1}\boldsymbol{K}_A\boldsymbol{K}_{Efd2}\end{bmatrix}\boldsymbol{\Delta E_d}
+
\begin{bmatrix}\mathbf{0}\\ -\boldsymbol{M}^{-1}\boldsymbol{K}_{\omega3}\\ -\boldsymbol{T}_{d0}^{-1}\boldsymbol{K}_{E'_q3}\\ -\boldsymbol{T}_A^{-1}\boldsymbol{K}_A\boldsymbol{K}_{Efd3}\end{bmatrix}\boldsymbol{\Delta E_q}
\tag{1}
$$

The internal dynamics of WPIG includes that of induction generator and converter controllers (if DFIG), which can be described by a set of first-order differential equations. In frequency domain, these equations can be converted and presented in the form of a SIMO controller as shown in Fig. 2, which will be explained in details in Section 3. The

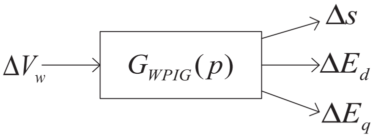

Fig. 2. Representation of WPIG internal dynamics in frequency domain.