Renewable Energy 93 (2016) 188–200

Contents lists available at ScienceDirect

Renewable Energy

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

An improved reduced-order model of an electric pitch drive system for wind turbine control system design and simulation

Hui Li [a,*], Chao Yang [a,b], Yaogang Hu [a], Xinglin Liao [a], Zheng Zeng [a], Chen Zhe [c]

[a] *State Key Laboratory of Power Transmission Equipment & System Security and New Technology, School of Electrical Engineering, Chongqing University, Chongqing 400044, China*

[b] *State Grid Jibei Electric Power Co., Ltd., Qinhuangdao Power Supply Company, Qinhuangdao 066000, China*

[c] *Institute of Energy Technology, Aalborg University, Aalborg East DK-9220, Denmark*

A R T I C L E I N F O

Article history:
Received 2 July 2015
Received in revised form
22 January 2016
Accepted 19 February 2016
Available online 3 March 2016

Keywords:
Electric pitch drive system
Loading simulations
Pitch angle controller design
Reduced-order model
Wind turbines

A B S T R A C T

To obtain satisfactory dynamic characteristics and enhance numerical simulation efficiency, an improved reduced-order transfer-function model of an electric pitch drive system (EPDS) for a wind turbine is proposed. First, a detailed transfer-function model of an EPDS is developed on the basis of its mathematical model. Thereafter, the improved reduced-order transfer-function model for an EPDS is derived from the detailed model by transfer-function approximation, sensitivity analysis, and block diagram reduction. The frequency-domain characteristics of the proposed model and their effects on the stability of the pitch angle control system are also analyzed and compared with that of a first-order transfer-function model. Finally, the dynamic characteristics of an EDPS using the improved model are analyzed and verified by a practical EPDS test platform. Furthermore, based on the FAST–MATLAB/Simulink co-simulation tool, simulation comparisons are performed on the loading characteristics of a wind turbine to further validate its availability in it. Results show that the improved model is superior to the first-order model for the performance analysis of a wind turbine pitch angle controller, and it also can meet the requirements of large-scale loading simulations for wind turbines both in terms of the precision and the time efficiency.

1. Introduction

The use of wind energy in power systems has been increasing rapidly over the last few decades. At the same time, the need for better cost-effective wind power plants has stimulated growth in wind turbine size and rated power. However, with increasing size, wind turbines become subjected to extreme structural loadings and fatigue [1,2]. To maintain a desired power capture profile, mitigate the structure loadings of a wind turbine, and regulate the output power of a wind turbine to the requirement of the connected power system, pitch angle control has been increasingly used in modern wind turbines [3]. The electric pitch drive system (EPDS), as the actuator of the pitch angle control system, has an obvious influence on wind turbine dynamics [3]. Therefore, to investigate that, design the pitch angle control system, and analyze the system performance, an adequate model for EPDS needs to be studied.

Different models of pitch drive systems have been introduced according to different research purposes. To design a pitch drive system and analyze its dynamic characteristics, a detailed model is necessary to show as much internal features of a pitch drive system as possible. Refs. [4,5] respectively propose detailed mathematical models for a DC machine and an induction machine (IM)-based EPDS by considering the detailed control strategy, electromagnetic transient of the machine, and drive train dynamics. Those detailed models could well show the internal features of an EPDS and that would make them efficient in designing a pitch drive system itself and make loading characteristic simulations of a wind turbine more realistic. However, they are nonlinear and high-order model with large number of variables and parameters, thus making them useless in the design and stability analysis of the pitch angle controller. Moreover, the use of those complex pitch drive system models in large-scale simulations of wind turbines, e.g., simulations on wind turbine loading characterizers, which usually involve hundreds or thousands of simulations that model different conditions, are time consuming and fallible. Furthermore, many internal features of in a pitch drive system are insignificant in the loading characteristic analysis of a wind turbine. Therefore, a simple pitch

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

http://dx.doi.org/10.1016/j.renene.2016.02.063
0960-1481/

drive system model is necessary to improve the design of wind turbine control and enhance the time efficiency of large-scale simulations for wind turbines. In Refs. [6,7], a pitch angle control is designed to maintain the desired power capture profile of a wind turbine under high wind speed on the basis of a simple first-order transfer-function model of a pitch drive system. In Refs. [8–13], by representing the pitch drive system as a second-order transfer-function model, the pitch angle controller is designed to mitigate the structure loadings of a wind turbine and regulate the output power of the wind turbine to the requirement of the connected power system. The first- or second-order model is simple enough for the design of wind turbine control. However, these models are too simple to show the dynamics characteristics of a pitch drive system because they neglect the position and speed control dynamics. Therefore, the performance of the designed pitch angle control system may be not as good as imagined. To investigate the dynamic characteristics of a wind turbine, a third-order transfer-function model of a pitch drive system is adopted from Ref. [14] to model a wind turbine. The third-order model cannot show the speed control dynamics of a pitch drive system because the regulation of the pitch speed is simplified by a first-order model. Therefore, wind turbine dynamics may not be shown well by using such a pitch drive system model because pitch speed dynamics may have an obvious effect on that, particularly on the mechanical loading characteristics of a wind turbine.

Therefore, considering that IM-based EPDS is widely applied in modern wind turbines because of its high reliability and low cost, we propose an improved reduced-order model for such an IM-based EPDS. In Section 2, a detailed transfer-function model of an EPDS is developed on the basis of its mathematical model. In Section 3, the improved reduced-order transfer-function model is derived from the detailed model. The frequency-domain characteristics of the proposed model and its effects on the stability of a wind turbine are analyzed and compared with those of a simple first-order transfer-function model. In Section 4, the improved pitch drive system model is verified by an experimental test and simulation comparisons with the first-order model. In Section 5, simulation comparisons are performed on loading characteristics of a wind turbine under the two different pitch drive system models to further validate the improved model. In Section 6, conclusions are drawn.

2. Detailed mathematical model and transfer-function model of an IM-based EPDS

Fig. 1 shows the principle schematic of an IM-based EPDS, which mainly consists of an induction machine, a driver, a controller, and a gearbox [5,15]. The detailed model of each subsystem is presented to form a detailed mathematical model of the EPDS. On the basis of the mathematical model, the detailed transfer-function model is developed in the following subsections.

2.1. Transient model of the EPDS induction machine

Considering the $d-q$ model of the IM in the reference frame rotating at synchronous speed ω_e, the voltage equations can be expressed as follows [16]:

$$\begin{aligned} u_{ds} &= R_s i_{ds} + p\psi_{ds} - \omega_e \psi_{qs} \\ u_{qs} &= R_s i_{qs} + p\psi_{qs} + \omega_e \psi_{ds} \\ u_{dr} &= 0 = R_r i_{dr} + p\psi_{dr} \\ u_{qr} &= 0 = R_r i_{qr} + \omega_{sl}\psi_{dr} \end{aligned} \quad (1)$$

Under the assumptions of linearity of the magnetic circuit, the flux equations can be expressed as follows:

$$\begin{aligned} \Psi_{ds} &= L_s i_{ds} + L_m i_{dr} \\ \Psi_{qs} &= L_s i_{qs} + L_m i_{qr} \\ \Psi_{dr} &= L_m i_{ds} + L_r i_{dr} \\ \Psi_{qr} &= L_m i_{qs} + L_r i_{qr} \end{aligned} \quad (2)$$

In Equations (1) and (2), u, i, ψ, R, and L denote the voltage, current, flux, resistance, and inductance, respectively. The s and r subscripts denote the variables or parameters associated with the stator and rotor circuits, respectively. The d and q subscripts denote the d- and q-axis components of the variables or parameters, respectively. L_m is the amplitude of the mutual inductance between the stator and rotor windings. $\omega_{sl} = \omega_e - \omega$ is the slip angular speed, where ω is the rotor speed and ω_e is the electrical speed of the stator. p denotes the differential operator.

2.2. Control strategy of the EPDS

Rotor-flux-oriented vector control is one of the most popular vector control strategies [16,17]. In this vector control strategy, the d-axis component i_{ds} of the stator current is aligned with the rotor field and the i_{qs} component is perpendicular to the i_{ds}. This is accomplished by choosing ω_e to be the speed of the rotor flux and locking the phase of the reference frame system such that the rotor flux is aligned precisely with the d-axis, thus resulting in the following:

$$\Psi_{dr} = \Psi_r, \quad \Psi_{qr} = 0 \quad (3)$$

From Equations (1)–(3), the electromagnetic torque of the IM can be given as follows:

$$T_e = \frac{n_p L_m}{L_r}\left(i_{qs}\psi_{dr} - i_{ds}\psi_{qr}\right) = \frac{n_p L_m}{L_r} i_{qs}\psi_{dr} \quad (4)$$

the rotor flux and slip angular speed ω_{sl} can be given as

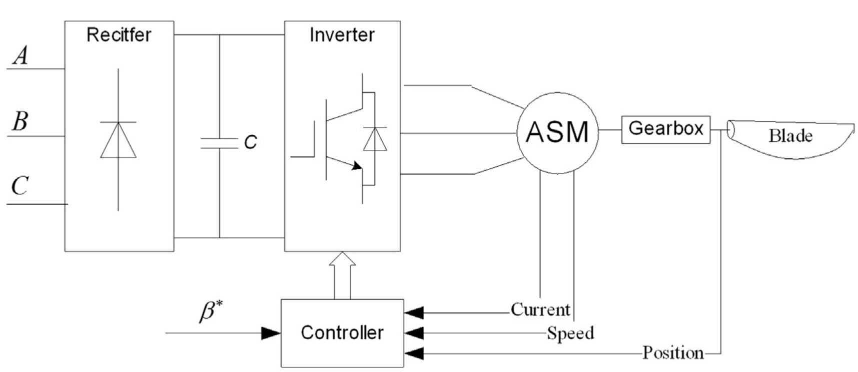

Fig. 1. Principle schematic of an IM-based EPDS.