Simulation Modelling Practice and Theory 18 (2010) 1032–1045

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

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

Hybrid modeling of DFIGs for wind energy conversion systems

Lingling Fan [a,*], Zhixin Miao [a], Subbaraya Yuvarajan [b], Rajesh Kavasseri [b]

[a] Department of Electrical Engineering, University of South Florida, Tampa, FL 33620, USA
[b] Department of Electrical and Computer Engineering, North Dakota State University, Fargo, ND 58105, USA

ARTICLE INFO

Article history:
Received 20 May 2009
Received in revised form 4 April 2010
Accepted 5 April 2010
Available online 10 April 2010

Keywords:
Wind Generation
Doubly Fed Induction Generator
Harmonics
Hybrid modeling

ABSTRACT

The synchronous reference frame is widely used in Doubly Fed Induction Generation (DFIG) modeling. In a DFIG, it is usually assumed that slip control is in place at the rotor-side converters to make sure that the injected rotor voltage at slip frequency gives a constant stator frequency (60 Hz or 50 Hz). In the analysis, the injected rotor voltages are directly expressed in the synchronous reference frame. In the cases where slip control is not available, the above modeling will not work. This paper implements a hybrid model (*dqabc*) of a DFIG. The key modeling idea is to use the frequencies of the injected rotor voltages as explicit inputs and further transform the injected rotor voltage into the synchronous reference frame. This allows one to model and simulate scenarios including: (i) acceleration via rotor injection, (ii) harmonic simulation for six-pulse rotor injection, and (iii) negative sequence compensation using rotor injection. Matlab/Simulink is used to perform the simulations of three cases listed above. Laboratory experiments on two of the cases confirm the validity of the model and simulation results.

1. Introduction

Doubly Fed Induction Generators (DFIGs) are widely used in wind generation. The synchronous reference frame is most often used in DFIG modeling. In a DFIG, it is usually assumed that slip control is in place at the rotor-side converters to make sure that the injected rotor voltage at slip frequency gives a constant stator frequency (60 Hz or 50 Hz). In the analysis, the injected rotor voltages are directly expressed in the synchronous reference frame [1–4]. Under the above assumption, the rotor voltage is a sinusoidal three-phase voltage with controllable magnitude and controllable frequency ($f_r = f_e - f_m$). In the cases where slip control is not available, the above modeling will not work.

The cases where slip control is not available are plenty. The acceleration of a DFIG subjected to an applied rotor voltage is the first example. The acceleration process of an induction machine through applied stator voltage is well known and has been presented in textbooks [5], while the acceleration of a DFIG through a constant-magnitude constant-frequency rotor injection is not well known.

The second example is where the injected rotor voltage is non-sinusoidal. Usually Sine Pulse Width Modulation (PWM) is employed to generate a three-phase sinusoidal rotor voltage. In order to reduce the switching losses, a six-step switching technique is used resulting in quasi-sine rotor voltage waveforms [6–8].

The third example is where harmonics are added to the injected rotor voltage to suppress the rotor current harmonics caused by the unbalanced stator conditions. The unbalanced stator conditions can cause rotor harmonics and torque ripples with significant magnitudes. Negative sequence compensation in rotor voltages is widely used as the control method to

* Corresponding author. Tel.: +1 813 974 2031.
E-mail addresses: linglingfan@usf.edu (L. Fan), zmiao@usf.edu (Z. Miao), subbaraya.yuvarajan@ndsu.edu (S. Yuvarajan), rajesh.kavasseri@ndsu.edu (R. Kavasseri).

1569-190X/$ - see front matter
doi:10.1016/j.simpat.2010.04.002

Nomenclature

f_r, ω_r	rotor frequency
f_s, ω_s	stator frequency
f_e, ω_e,ω_b	nominal frequency (60 Hz or 50 Hz)
f_m, ω_m	corresponding electrical frequency of the rotating speed
s	slip $s = \frac{\omega_e - \omega_m}{\omega_e}$
v_{qs}, v_{ds}	q-axis and d-axis stator voltages
i_{qs}, i_{ds}	q-axis and d-axis stator currents
v'_{qr}, v'_{dr}	q-axis and d-axis rotor voltages referred to the stator windings
i'_{qr}, i'_{dr}	q-axis and d-axis rotor currents referred to the stator windings
X_{ss}, X'_{rr}	stator and rotor self inductive reactances
X_{ls}, X'_{lr}	stator and rotor leakage reactances
X_M	mutual reactance
r_s, r'_r	stator and rotor resistances

Superscripts:

e	synchronous reference frame
r	rotor reference frame

mitigate the harmonics in rotor currents and torque in [9–13]. The essence of the technique is to use a voltage source type inverter to generate two sinusoidal voltages, one at the slip frequency $s\omega_e$ and the other at a frequency of $(2 - s)\omega_e$.

A DFIG model that can accommodate these cases is necessary to study the behavior of DFIGs through computer simulation. In this paper, a DFIG model is developed to handle various scenarios of the injected rotor voltage. In this model, the frequency and amplitude of the injected rotor voltage become explicit inputs. Alternatively, the injected rotor voltage is expressed in *abc* frame. This kind of modeling approach (*dqabc*) has been applied in slip energy recovery induction motor drives [14–17]. In [14], a hybrid model is used which retains the actual rotor phase variables but transforms those of the stator only. The starting transients of slip energy recovery induction motor (IM) drives when started directly with the rotor rectifier was examined. The hybrid modeling was also used in [15] in simulations of the harmonic content of waveforms in a slip energy recovery induction motor drive. In [16], a hybrid model of the induction motor and a dynamic model of the rotor rectifier are used to derive an expression of the overlap angle. A reference frame based model and a hybrid model were compared in [17] and it is found that the hybrid modeling is more accurate by considering harmonics in the rotor variables.

The objective of this paper is to develop a hybrid model for DFIG-based wind energy system and further illustrate the usage of the model. The applications of the hybrid model of DFIGs include: (1) simulations of the starting transients of a DFIG when started directly with the rotor voltage injection and (2) harmonic waveform simulation with non sinusoidal rotor injection. In addition, this paper will simulate negative sequence compensation through rotor injection to mitigate rotor current harmonics and torque ripples caused by unbalanced stator conditions.

The rest of the paper is organized as follows. Section 2 gives the induction machine model in the synchronous reference frame. Section 3 presents the principle of modeling rotor injection in DFIG. Three case studies, namely, DFIG acceleration through rotor injection, harmonic simulation due to quasi-sine rotor injection, and harmonic simulation of negative sequence compensation from the rotor voltages are simulated using the proposed model. Conclusions are given in Section 5.

In a previous paper [18], harmonic analysis of a DFIG due to six-pulse rotor injection and unbalanced stator conditions is presented. Quantitative (analytical) results are given and verified by the simulation and experimental results. The simulation technique used for verification in [18] is presented in this paper. Compared with [18], this paper illustrates the modeling and simulation procedure to analyze DFIG behavior under special circumstances. Case studies are presented to demonstrate the application of the hybrid modeling technique and a technique is proposed to compensate the effect of unbalanced stator conditions.

2. DFIG model

The DFIG model can be written in the following form based on the voltage and current equation of an induction machine presented in Appendix:

$$\dot{X} = AX + BU, \tag{1}$$

where

$$X = \left[i^e_{qs}, i^e_{ds}, i^e_{os}, i'^e_{qr}, i'^e_{dr}, i'^e_{0r}\right]^T,$$

$$U = \left[v^e_{qs}, v^e_{ds}, v^e_{0s}, v'^e_{qr}, v'^e_{dr}, v'^e_{0r}\right]^T.$$