Electric Power Systems Research 93 (2012) 16–23

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

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

DFIG-based fuzzy sliding-mode control of WECS with a flywheel energy storage

D. Kairous [a,*], R. Wamkeue [b]

[a] Department of Applied Sciences, Université du Québec à Chicoutimi (UQAC) Québec (QC), G7H 2B1 Canada
[b] Department of Applied Sciences, Université du Québec en Abitibi-Témiscamingue (UQAT) Québec (QC), J9X 5E4 Canada

ARTICLE INFO

Article history:
Received 31 July 2011
Received in revised form 27 March 2012
Accepted 4 July 2012
Available online 24 July 2012

Keywords:
Energy storage
Flywheel
Fuzzy control
Induction machine
Sliding mode control and wind power generation

ABSTRACT

In this paper the so-called sliding-mode control (SMC) technique used with fuzzy control is applied to control a variable speed wind energy conversion system (WECS) with a doubly fed induction generator (DFIG). The paper also points out interesting performances of the double-fed induction machine (DFIM) used as a flywheel energy storage system (FESS). In fact, adjusting the rotor speed can allow the induction machine to release kinetic energy to the power system or to absorb this energy from the utility grid. The DFIM enables decoupled control of system active and reactive powers in both steady and transient states. The effectiveness of the proposed DFIG-based WECS control approach along with FESS is demonstrated with computer simulation results

1. Introduction

Renewable energy is increasingly attractive in solving global problems such as environmental pollution and energy shortage. Among a variety of renewable-energy resources, wind power is drawing the most attention from government, academia, utilities and industry. The disadvantage of wind power generation is that it is intermittent, depending on weather conditions, which means that short-term energy storage is necessary for a smooth power output from a wind turbine [1].

Compared with the wind turbines with synchronous generators, the doubly fed induction generator (DFIG) based wind generation technology has several advantages such as flexible active and reactive power control capabilities, reduced converter costs and lower power losses [2]. The DFIG is directly connected to the grid at the stator terminals and the rotor terminals are connected to the grid via a variable-frequency AC/DC/AC converter. During the wind speed variation, controlling two back-to-back four quadrant power converters connected between the rotor side and the grid side can make the rotor flux rotate from a sub-synchronous speed to a super-synchronous speed. The DFIG can produce and inject constant-frequency power to the grid by controlling the rotor flux. The power converter only needs to handle a fraction (typically 25–30%) of the total power to achieve a full control of the generator. To address the intermittency problem, this paper presents an integrated DFIG based power generation including a flywheel energy storage system with another doubly fed induction machine (DFIM). Despite extensive research efforts on new batteries over the past two decades, available batteries are limited in their usefulness as a temporary energy storage device.

Research experts have recognized that the flywheel offers important advantages for reducing peak power demands together with a longer service life. The need for a low cost, long life cycle, small size, and high power density energy storage systems has made the temporary flywheel energy storage system (FESS) a viable solution to the power quality problem. Many surveys have shown that the majority of voltage sags and momentary interruptions last less than 3 s. In such a context, the energy storage systems are required to effectively provide a short burst of power [3,4].

Many advantages are offered by this emerging technology in aerospace applications, for space vehicles, flywheel traction electric transfer and also been considered for the stabilization of electric power system transients [5].

Attention has been paid to a flywheel energy storage system based on a doubly fed induction machine for the power conditioning purpose. It is also called an "adjustable speed rotary condenser" which is able to control active and reactive powers. In contrast, the conventional "synchronous-speed rotary condenser" only controls the reactive power control. The secondary (rotor) windings of the doubly fed induction machine are excited by three-phase low-frequency AC currents, which are supplied via slip rings by a variable-frequency AC/DC/AC converter.

Adjusting the rotor speed can allow the induction machine to release the kinetic energy to the power system or to absorb this energy from the utility grid. It appears that the flywheel energy

* Corresponding author. Tel.: +1 819 762 0970.
E-mail addresses: djilali.kairous@uqat.ca (D. Kairous), rene.wamkeue@uqat.ca (R. Wamkeue).

0378-7796/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsr.2012.07.002

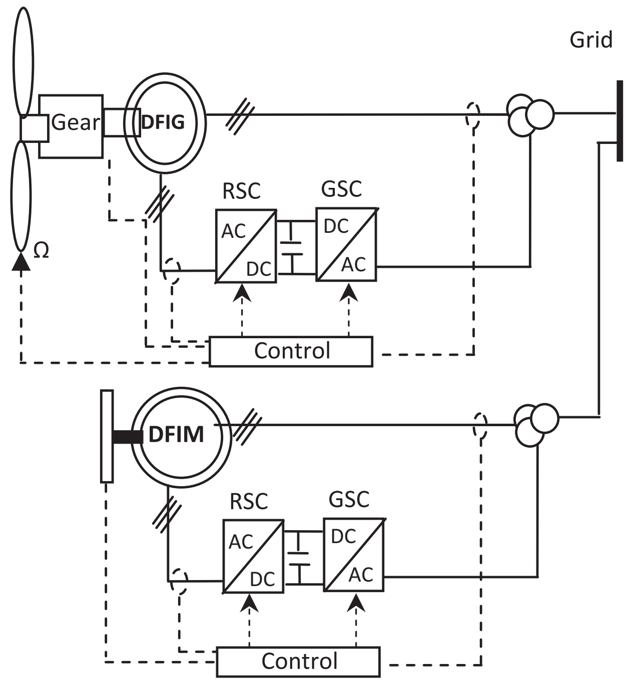

Fig. 1. VSWG FESS assembly under study.

storage system is more suitable for repetitively short period absorbing and releasing electric energy than a battery energy storage system [6].

Since the approach under study is a time-variable nonlinear system, traditional control methods using PID controllers do not provide interesting results [7,8]. Traditional PID controllers only guarantee the desired closed-loop response at the operating point for which the controller was designed. In addition, with a change of system parameters, it is possible that the system works in the unstable region [9].

In fact, during the last decade, the FLC has been selected as suitable control solution in the field of power electronics and drives [10,11]. Among the advantages provided by this control approach over the conventional controllers in other hand it does not require accurate mathematical model. It can thus work with inaccurate inputs, handle nonlinear model systems and easily reach performances of ideal digital PI controllers [12]. On the other hand, SMC has demonstrated great interests in flux, speed and position control (even with mechanical sensorless techniques) of induction machines [13]. The SMC appears as a simple way to design robust controllers for electrical drives, a powerful technique to eliminate sensors in electrical machine drives. Furthermore, the SMC does not require many computational operations and remains insensitive to plant parameters variations [14].

Accordingly, this paper aims at combining the advantages of FLC and SMC for robust control DFIG based WECS. This approach has been successful applied in [15] for robust control of six phase induction machine with open phases. Integrating the advantages of the sliding-mode and fuzzy controls will not only make the system more robust but will also seriously minimize vibrations. This paper applies fuzzy sliding-mode control to adjust the DFIM flux and the torque produced together with the associated DFIG wind system [16].

The next section presents the entire system under study. The modeling and control strategy of the DFIM are dealt with in Section 3, while Sections 4 and 5 focus on the design of the SMC and fuzzy control, respectively. In Section 6, details on the space vector modulation (SVM) approach used in the paper are outlined while the following section presents simulation results for the validation of the DFIM control framework. Section 8 concludes this study and announces the next steps in future investigations.

2. Description of studied system

The basic configuration of the whole system is presented in Fig. 1. The rotor of the DFIG is connected to the grid through two back-to-back bridge converters. The PWM grid-side converter (GSC) is used to control the DC-link voltage and keep it constant regardless of the magnitude and direction of the rotor power [17]. The PWM rotor-side converter (RSC) of the DIFG is used to generate the optimal active power depending on the wind speed and turbine characteristics. However, the PWM rotor-side converter of the DIFM is used to generate the optimal smooth active power at the grid. The great interest of this system is its ability to simultaneously capture the maximum energy from the wind fluctuation, control the active and reactive powers and smooth the output power of the grid. The transformer is considered to be linear (magnetic saturation not taken into account in the study). It is assumed that the average PWM back-to-back converter reproduces the reference voltages generated by the control scheme without losses.

3. Modeling and control of the FESS

The electrical equations of the wound-rotor induction machine (DFIG) in the d–q reference frame are as follows [18]:

$$V_{dqs} = R_s I_{dqs} + \frac{d\varphi_{dqs}}{dt} + \Xi\,\omega_s \varphi_{dqs} \tag{1}$$

$$V_{dqr} = R_r\, I_{dqr} + \frac{d\varphi_{dqr}}{dt} + \Xi\,\omega_r\,\varphi_{dqr} \tag{2}$$

with:

$$\varphi_{dqs} = L_s\, I_{dqs} + M I_{dqr} \tag{3}$$

$$\varphi_{dqr} = L_r\, I_{dqr} + M\, I_{dqs} \tag{4}$$

$$\Xi = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \tag{5}$$

subscripts d and q refer to the d- and q-axes, respectively and subscripts s and r to the stator and rotor of the DFIG respectively; ω_s,and ω_r (in rad/s) are the stator and rotor variable pulsations respectively; V_{dq}, I_{dq} and φ_{dq} are voltage current and flux vectors respectively in the d–q reference frame; R_s and R_r are stator and rotor resistances; L_s and L_r are the stator and the rotor leakage inductance and M is the magnetizing inductance. Ξ is the coupling-axes matrix.

The electromechanical equation is expressed by:

$$J\frac{d\Omega}{dt} + f\Omega = T_e - T_r \tag{6}$$

$$T_e = p\left(\varphi_{ds} I_{qs} - \varphi_{qs} I_{ds}\right) \tag{7}$$

where p is the number of the pole pair, T_r is the mechanical torque, T_e is the electrical torque, J is the inertia constant, Ω is the rotor speed, and f is the friction coefficient.

In an aim to decouple the torque and the flux, the stator flux vector will be aligned with the d-axis. So, by neglecting the stator resistance and assuming that the stator flux $\varphi_{ds} = \varphi_s$ is maintained constant, we then have:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} \approx \omega_s \varphi_{ds} = V_s \end{cases} \tag{8}$$