Electrical Power and Energy Systems 49 (2013) 234–242

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

Optimal tracking and robust power control of the DFIG wind turbine

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ARTICLE INFO

Article history:
Received 16 March 2011
Received in revised form 9 December 2012
Accepted 24 December 2012
Available online 24 February 2013

Keywords:
Wind turbine
Doubly Fed Induction Generator (DFIG)
Power control
Sliding mode control
Fuzzy MPPT algorithm

ABSTRACT

In the present paper, an optimal operation of a grid-connected variable speed wind turbine equipped with a Doubly Fed Induction Generator (DFIG) is presented. The proposed cascaded nonlinear controller is designed to perform two main objectives. In the outer loop, a maximum power point tracking (MPPT) algorithm based on fuzzy logic theory is designed to permanently extract the optimal aerodynamic energy, whereas in the inner loop, a second order sliding mode control (2-SM) is applied to achieve smooth regulation of both stator active and reactive powers quantities. The obtained simulation results show a permanent track of the MPP point regardless of the turbine power-speed slope moreover the proposed sliding mode control strategy presents attractive features such as chattering-free, compared to the conventional first order sliding technique (1-SM).

1. Introduction

During the last decades, especially after the oil crisis in the 1970s, global interest for clean and renewable energy sources has been growing intensively. Wind energy in particular, has received a strong impulse, reflected in great technology advances regarding reliability, cost-efficiency and integration to the grid of the wind energy conversion systems (WECSs). Wind turbines generate about 1.5% of the word electricity consumption, with an installed capacity of 121 GW by the end of 2008 comprising more than 70 countries [1].

These wind turbines are all based on variable speed operation using a Doubly Fed Induction Generator (DFIG) or a direct driven synchronous generator (without gearbox).

The doubly fed induction generator is used in several wind energy conversion systems. This machine has proven its efficiency due to qualities such as robustness, cost and simplicity. It offers several advantages including variable speed operation (±33% around the synchronous speed), and four-quadrant active and reactive power capabilities Such system also results in lower converter cost and lower power losses compared to a system based on a fully fed synchronous generator with full-rated converter. Moreover, the generator is robust and requires little maintenance [2–9].

The control law of the converter can be applied in order to extract maximum power of the wind turbine for differents wind speeds.

Many papers have been presented with different control schemes of DFIG. These control schemes are generally based on vector control concept (with stator flux or voltage orientation) associated with classical controllers [10–16].

With the improvements technologies in materials, power electronics and blade design, classical controllers for WECS can be updated by the development of more efficient strategies based on modern control techniques such as: fuzzy logic control [17–19], robust control [20–22], adaptive control [23] and sliding-mode control [24–27].

Among these control strategies, sliding mode (SM) control emerges as an especially suitable option to deal with variable speed operating WECS. This control technique has proven to be very robust with respect to system parameter variations and external disturbances.

In this paper, an optimal operation of a grid-connected variable speed wind turbine, based on a doubly fed induction generator is presented. The proposed control algorithms focus two main goals: a permanent track of the available maximum wind power, and a smooth regulation of the stator active and reactive powers exchanges between the machine and the grid.

In Section 2, explicit models of the different sub-systems are described. In Section 3, the proposed control algorithms are detailed precisely, while in Section 4 simulation results are presented and discussed.

2. System description and modeling

The topology of the wind energy conversion system (WECS) under consideration in this paper is depicted in Fig. 1. It is constituted

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http://dx.doi.org/10.1016/j.ijepes.2012.12.014

Nomenclature

V_w	wind speed, m s^{-1}	P_s, Q_s	active and reactive statoric powers, W (Var)
ρ	air density, kg m^{-3}	T_{em}	DFIG torque, N m
R	rotor radius, m	d, q	synchronous reference frame index
λ	tip-speed ratio	$V_{sd,q}$	stator d–q frame voltage, V
C_P, C_T	power and torque coefficients	$V_{rd,q}$	rotor d–q frame voltage, V
P_a	aerodynamic power, W	$I_{sd,q}$	stator d–q frame current, A
T_a	aerodynamic torque, N m	$I_{rd,q}$	rotor d–q frame current, A
Ω_t	aeroturbine rotor speed, rad s^{-1}	$\varphi_{sd,q}$	stator d–q frame flux, Wb
Ω_m	generator speed, rad s^{-1}	$\varphi_{rd,q}$	rotor d–q frame flux, Wb
Ω_s	synchronous generator speed, rad s^{-1}	R_s, R_r	stator and rotor Resistances, Ω
f	turbine total external damping, N m rad^{-1} s	L_s, L_r	stator and rotor Inductances, H
J	turbine total inertia, kg m^2	L_m	mutual inductance, H
G	gearbox ratio;	σ	leakage coefficient,
f_t, f_g	rotor and DFIG external damping, N m rad^{-1} s	ω_s, ω_r	synchronous speed and Angular speed, rad s^{-1}
J_t, J_g	rotor and DFIG inertia, kg m^2	s	generator slip

of a small scale windmill and a Doubly Fed Induction Generator (DFIG) coupled to a three phase grid.

In such configuration, the stator winding is directly connected to the grid, whereas, two converters are inserted between the rotor side and the utility grid to permit a power exchange between the grid and the machine in sub-synchronous speed. So the grid side converter (GSC) works as a rectifier, and the rotor side converter (RSC) operates to control the DFIG for independent control of active/reactive powers quantities.

In the case studied in this paper, two operation modes are distinguished: when the aerodynamic power is not enough to reach the synchronous speed, the system operates at mode 1: maximum power extraction, whereas, if the wind speed exceeds the rated value, the system switches to mode 2: power limitation, which leads the DFIG to provide its rated power below synchronous speed.

The models of the different components of the wind-turbine generation system are described below:

2.1. Wind turbine modeling

The aerodynamic power captured by the aeroturbine rotor is given by [28],

$$P_a = 0.5\rho\pi R^2 V_w^3 C_P(\lambda,\beta) \quad (1)$$

C_P is the power coefficient which is a nonlinear function of the tip speed ratio (TSR) λ

$$C_P\ (\lambda) = a_0 + a_1\lambda + a_2\lambda^2 + a_3\lambda^3 + a_4\lambda^4 + a_5\lambda^5 \quad (2)$$

The TSR is defined as the ratio between the linear blade tip speed and the wind speed, expressed as:

$$\lambda = \frac{R\Omega_t}{V_w} \quad (3)$$

Then the aerodynamic torque is given by

$$T_a = \frac{P_a}{\Omega_t} = 0.5\rho\pi R^3 V_w^2 C_T(\lambda,\beta) \quad (4)$$

where

$$C_T(\lambda,\beta) = \frac{C_P(\lambda,\beta)}{\lambda} \quad (5)$$

The $C_p(\lambda)$ characteristic is illustrated in Fig. 2. This figure indicates that there is one specific λ_{opt} at which the turbine is most efficient. Normally a variable speed wind turbine follows the C_{pmax} to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{opt}.

Fig. 3 shows the power rotational speed curves of 7.8 kw wind turbine considered in the present paper under different wind speeds. The dotted line indicates the optimal power points P_{aopt} where the C_P coefficient is kept at its maximum value.

If a perfectly rigid low-speed shaft is assumed, a single mass model of the turbine may be considered [28].

$$J\dot{\Omega}_t + f\Omega_t = T_a - GT_{em} \quad (6)$$

where

$$J = J_t + G^2 J_g$$

$$f = f_t + G^2 f_g$$

$$G = \frac{\Omega_m}{\Omega_t}$$

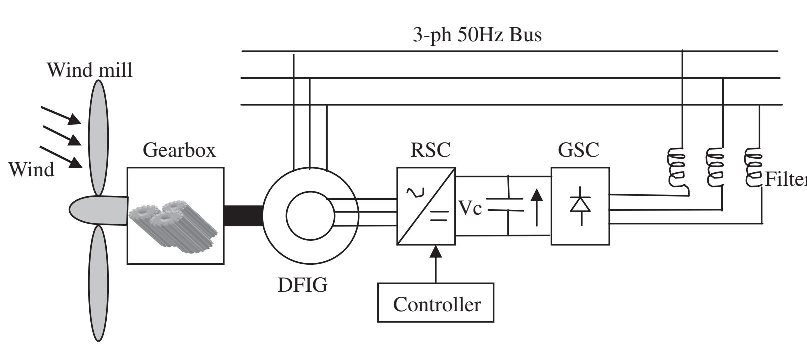

Fig. 1. Block diagram of conventional wind generator with a DFIG.