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Implementation of MRAC controller of a DFIG based variable speed grid connected wind turbine

Sabrina Abdeddaim [a,*], Achour Betka [a], Said Drid [b], Mohamed Becherif [c]

[a] *LGEB Laboratory, Electrical Engineering Department, Biskra University, Algeria*
[b] *LSPIE Laboratory, Electrical Engineering Department, Batna University, Algeria*
[c] *FCLab FR CNRS 3539, Femto-ST UMR CNRS 6174, UTBM, France*

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ABSTRACT

This paper presents the design and the implementation of a model reference adaptive control of the active and reactive power regulation of a grid connected wind turbine based on a doubly fed induction generator. This regulation is achieved below the synchronous speed, by means of a maximum power-point tracking algorithm. The experiment was conducted on a 1 kW didactic wound rotor induction machine in association with a wind turbine emulator. This implementation is realized using a dSPACE 1104 single-board control and acquisition interface. The obtained results show a permanent track of the available maximum wind power, under a chosen wind speed profile. Furthermore the proposed controller exhibits a smooth regulation of the stator active and reactive power amounts exchanged between the machine and the grid.

1. Introduction

Among renewable energy sources, wind power recorded the fastest growth in the last decade. Under an advanced wind energy projection, coupled with energy saving ambitions, wind power will be able to supply 29.1% of the world electricity need by 2030 and 34.2% by 2050 [1,2].

Currently, the doubly-fed induction generator (DFIG) is widely used in variable speed wind generation systems. This machine has proven its efficiency due to various qualities such as robustness, cost and design simplicity. It offers several advantages including variable speed operation (±33% around the synchronous speed) and four-quadrant active and reactive power capabilities. The system also entails lower converter cost and less power losses compared to its competitive plant based on a fully fed synchronous generator with a full rated converter [3–6].

The increase of the wind turbines plant based on the (DFIG) has led electrical engineering researchers to carry out investigations, in order to improve the electromechanical conversion efficiency and the provided power quality.

To reach these aims, many experimental platforms were developed and used to test some theories and simulation studies and to avoid any damage on the real system [7–13]. Many works used a controlled DC motor to emulate the behavior of a VSWGS connected to the electrical grid and hence, to test various maximum power point tracking (MPPT) algorithms [14–17]. Other works compared different robust controllers to optimize the active and reactive power amounts [18–27]. Further works [28–30] dealt with the synchronization problem, in order to smoothly, connect the DFIG stator to the grid. In this way, the stator voltage, frequency and phase-angle have to be properly adjusted to synchronize with the grid voltage.

In the present paper, an optimal operation of a small scale grid connected wind turbine system based on a DFIG is presented. In fact, the proposed control algorithms permit to fulfill the two main goals:

- As a prime mover, a separately excited DC motor is controlled via a buck chopper to reproduce the aerodynamic characteristic of a wind turbine (the aerodynamic torque as function of the mechanical speed).
- The common field oriented control of the DFIG is applied to separately regulate the stator active and reactive power exchanged with the grid.

Proportional-integral (PI) controllers are the most commonly used, however selection of controller gains is not easy and is usually subject to continuous adjustment. Very often, the gains obtained analytically or by simulation do not work well in practice. There are several causes for this: floating of DFIG parameters with the change in external conditions, saturation, noise, delays, imperfections in signal acquisition and improper field orientation.

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* Corresponding author. Tel.: +213 773535368.
E-mail addresses: s_abdeddaim@yahoo.fr (S. Abdeddaim), betkaachour@gmail.com (A. Betka), s_drid@yahoo.fr (S. Drid), mohamed.becherif@utbm.fr (M. Becherif).

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Nomenclature

P_w (W)	aerodynamic power
ρ (kg m^{-3})	air density
R (m)	rotor radius
V_w (m/s)	wind speed
C_p	power coefficient
λ	tip speed ratio
Ω_t (rad/s)	the turbine angular speed.
R_r (Ω)	rotor resistance
R_s (Ω)	stator resistance;
L_m (H)	magnetizing inductance;
L_s (H)	stator self-inductance;
L_r (H)	rotor self-inductance;
σ	leakage factor;
φ_{sd}, φ_{sq} (Wb)	stator d–q flux linkage;
φ_{rd}, φ_{rq} (Wb)	rotor d–q flux linkage;
I_{ms}, I_{sd}, I_{sq}, I_{rd}, I_{rq} (A)	magnetizing, stator d–q axis currents, rotor d–q axis currents
V_{sd}, V_{sq} (V)	stator d–q voltages;
V_{rd}, V_{rq} (V)	rotor d–q voltages;
V_{gd}, V_{gq} (V)	grid d–q voltages.
V_{DC} (V)	DC voltage.
P_s (W), Q_s (VAR)	stator active and reactive powers.
P_{sref} (W), Q_{sref} (VAR)	Reference stator active and reactive powers.
V^*_{rd}, V^*_{rq} (V)	rotor reference d–q voltages.
I_{ra}, I_{rb}, I_{rc} (A)	rotor phase currents
n_{mes}, n_{ref} (r/mn)	measured, reference DC speed.
ω_s, ω_r (rad/s)	synchronous and generator angular frequency
$S\omega_s = \omega_{sli}$	slip angular frequency.
θ_r, θ_s, θ_{sli} (rad)	rotor, stator and slip angle
I_{rdqm} (A)	d–q rotor current output of model reference
I_{rdq} (A)	measured d–q rotor current.
I_{rdqref} (A)	d–q rotor current references
P_{dq}	d–q disturbances.
edq	d–q current tracking errors

Furthermore the decoupled condition is only satisfied if the grid voltage is constant and the derivative of stator flux is neglected. These PI controllers can provide good dynamic response during nominal conditions, but their performance may be degraded during grid disturbances which mean that the stator flux is not constant [31,32]. To overcome these drawbacks, an implementation of a model reference adaptive control for the DFIG side converter is presented. The active power quantity is controlled to fit the wind speed profile, in order to track permanently the maximum aerodynamic power, whereas no reactive power control will be exchanged between the two power sides.

The paper is organized as follows: In Section 2, explicit models of the different sub-systems are given. In Section 3, the proposed MRAC control algorithm used in power regulation are properly detailed; whereas in Section 4 experimental results are given and discussed.

2. System modelling

In Fig. 1 is displayed a topology of the studied wind energy conversion system. The wind turbine is simulated via a DC machine, emulating the aerodynamic torque. The DFIG stator is directly connected to the grid via a synchronizing switch K_1 to supply the active and reactive powers. In the rotor circuit, two converters are inserted between the rotor side and the utility grid. In the present case, the DFIG operates in sub-synchronous speed, so the grid side converter (GSC) works as a rectifier, whereas the rotor side converter (RSC) operates to control the DFIG for both, synchronizing process, and independent control of active/reactive power quantities.

In the derivation of the system modelling, the DFIG is assumed to be unsaturated, and with no core loss.

2.1. Model of the turbine

The turbine is made up of three-bladed rotor and a hub. Through the turbine, wind energy is transformed into mechanical energy that turns the main shaft of the generator. The aerodynamic power P_w extracted by the wind turbine is given by [33]:

$$P_w = 0.5\rho\pi R^2 V_w^3 C_p(\lambda,\beta) \tag{1}$$

C_p is the wind turbine power coefficient, which is a nonlinear function of the tip speed ratio (TSR) λ. The accurate computation of the power coefficient requires the use of blade-element theory and the knowledge of blade geometry. These complex issues are normally empirically considered. In this paper, the blades orientation is not considered, so the power coefficient is expressed by [34]:

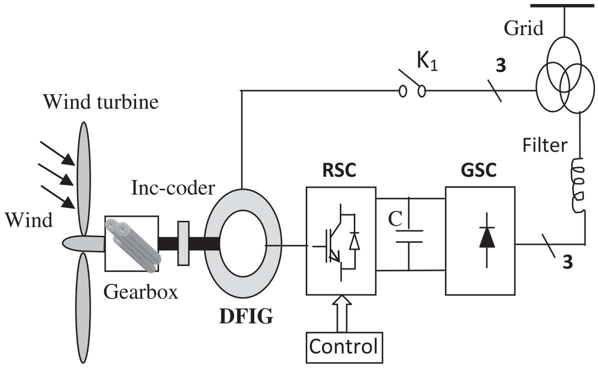

Fig. 1. DFIG configuration for wind turbine.

$$C_p(\lambda) = a_0 + a_1\lambda + a_2\lambda^2 + a_3\lambda^3 + a_4\lambda^4 + a_5\lambda^5 \tag{2}$$

The tip speed ratio λ is defined as the ratio between the linear blade tip speed and the wind speed:

$$\lambda = \frac{R\Omega_t}{V_w} \tag{3}$$

The power extracted from the wind is maximized if the rotor speed is such that C_p is maximum (C_{pmax}), which occurs for a determined tip speed ratio (λ_{opt}). The DFIG wind turbine control acts to keep the rotor speed in its optimum value and hence, to maximize the output power in a wide range of wind speeds, according to the following equation:

$$\Omega_{topt} = \frac{\lambda_{opt} V_w}{R} \tag{4}$$

$$P_{opt} = K_{opt}\Omega_t^3 \tag{5}$$

$$\text{where}: \quad K_{opt} = 0.5\rho\pi R^5 C_{pmax}/\lambda_{opt}^3 \tag{6}$$

P_{opt} is the optimal power that can be extracted from the wind.