Nonlinear Control of a Variable Speed Wind Generator

A. El magri, F. Giri*, A. Abouloifa, A. Elfadili

All authors are with the GREYC Lab, University of Caen, Caen, France.
* Corresponding author: (e-mail: fouad.giri@ unicaen.fr)

Abstract: we are considering the problem of controlling wind turbine synchronous generators driven through AC/DC rectifiers and DC/AC inverters. The control objectives are threefold: (i) forcing the turbine speed to track a reference signal, (ii) regulating the DC Link voltage, (iii) enforcing power factor correction (PFC) with respect to the power network. First, a nonlinear model of the whole controlled system is developed in the Park-coordinates. Then, a nonlinear multi-loop controller is synthesized using the backstepping design technique. A formal analysis based on Lyapunov stability and average theory is developed to describe the control system performances. In addition to closed-loop global asymptotic stability, it is proved that all control objectives (turbine speed tracking, DC link voltage regulation, and unitary power factor) are asymptotically achieved up to small harmonic errors (ripples). The amplitudes of these harmonic errors depend on the power network frequency: the larger the power net frequency the smaller the error amplitudes. The above results are confirmed by simulations which, besides, show that the proposed regulator is quite robust with respect to uncertain changes of wind speed.

Keywords: Control system analysis, Nonlinear control systems, Synchronous generators, AC/DC/AC converters, Wind power.

1. INTRODUCTION

Owing to its energy renewable nature and reduced environmental problems, wind power is playing an increasingly important role in electricity generation. The growth of the world-wide wind-turbine market in the last five years has been around 30% a year (Chen, Z et al 2006). Most wind turbines operate at a constant speed (with a tolerable variation of 1-2%). Then, the aerodynamic performance can only be maximal for a unique wind speed. Therefore, there is a considerable interest in using variable speed wind turbines. Indeed, these can be driven constantly near to the optimum tip-speed ratio λ_{opt} (Fig.1) through turbine rotor speed control. Specifically, rotor speed must follow wind-speed variations in low and moderate velocities in order to maximize aerodynamic efficiency. As a matter of fact, variable speed wind turbines have the potential to maximize energy generation.

In this paper, the focus is made on the generation system of Fig 2. This includes a permanent magnet synchronous generator (PMSG) that converts wind turbine power to output voltage whose amplitude and frequency vary with wind speed. Permanent magnet synchronous generators offer several benefits, in wind power applications, due to their high power density, high efficiency (as the copper losses in the rotor disappear), and absence of gearbox and reduced active weight. All these features make it possible to achieve with PMSG's a high performance variable speed control and highly reliable operation conditions (reduced need for maintenance).

The three-phase variable frequency and amplitude voltage generated from the wind turbine is rectified using a back-to-back rectifier-inverter (AC/DC/AC IGBT-based PWM converter), connected through a DC power transfer link (Fig 2). The AC side of the rectifier is connected to the stator of the PMSG; the inverter (DC/AC) output is directly tied to the grid.

The controlled system, consisting of a PMS generator an AC/DC converter and a DC/AC inverter, has to be controlled to achieve varying speed reference tracking. The generator speed reference (ω_{ref}) must be updated online, in function of the current wind velocity (w_{win}), to maximise the generated power. The point is that such system behaves as a nonlinear load vis-à-vis to the AC line (grid). Then, undesirable current harmonics are generated in the AC line which results in reduced inverter efficiency, induced voltage distortion in the AC line and electromagnetic compatibility problems. To overcome this drawback, the control objective must not be limited only to wind speed control, it should also includes the rejection of current harmonics. The last requirement is referred to power factor correction (PFC), (Singh B., et al G. 2006). Most of the previous works neglected, totally or partly, the dynamics of the AC/DC/AC converters, (e.g. S. Sivrioglu, et al, 2008). The focus was generally made on the set 'generator-AC/DC converter', (B. Boukhezzar, et al, 2006), (K. E. Johnson, et al, 2006), (K. Ohyama, et al, 2007). Ignoring the DC/AC inverter in the development of a control strategy is criticized at least from two viewpoints. First, such development relies on the assumption that the DC voltage is constant. The problem is that a perfect regulation of the rectifier output voltage can not be met ignoring the rectifier load which is nothing other than the set 'DC/AC inverter - grid'. The second drawback of the previous control strategy lies in the entire negligence of the PFC requirement.

In the present work, we are developing a new multiloop control strategy that deals simultaneously with both controlled subsystems: the combination 'AC/DC converter - generator' and the 'DC/AC inverter'. The main feature of our control design is threefold:

i. A bi-variable loop is first designed to enforce the wind velocity to track its varying reference value and to regulate the d-component of stator current to zero;

ii. A current loop is designed to control the output current (PFC);

iii. A voltage loop is designed that regulates the voltage at the DC link.

All loops are designed using the backstepping technique and Lyapunov design, (Krstic M, et al, 1995). A theoretical analysis will prove that the four-loop controller thus described actually stabilizes (globally and asymptotically) the controlled system and does achieve its tracking objectives with a good accuracy. More precisely, it is shown that the steady-state tracking errors corresponding to generator speed, stator current d-component, inverter output current and rectifier output voltage, are harmonic signals and their amplitudes depend on the net frequency: the larger the net frequency the smaller the error amplitudes. This formally establishes the existence of the so-called ripples, which are usually observed in similar practical applications, and proves why this phenomenon is generally insignificant. These theoretical results are obtained making a suitable use of different automatic control tools e.g. averaging theory and Lyapunov stability (Khalil H, 2002). The paper also includes a simulation study confirming the above theoretical results and, besides, shows that the controller compensates well to disturbing effects due wind speed changes.

The paper is organized as follows: the controlled system is modeled and given a state space representation in Section 2; the controller designed in Section 3 where its performances are theoretically analyzed; the controller performances are further illustrated in Section 4 through numerical simulations; a conclusion and a reference list end the paper. First, a list of notations is given hereafter to alleviate the paper presentation.

Notation list

L	*stator winding inductance*
R	*resistance of the stator windings*
i_d, i_q v_d, v_q	*d- and q- axis currents and voltages*
ω	*angular velocity of the rotor*
p	*number of pole pairs*
T_g	*input torque*
J	*total inertia of PMSG rotor*
F	*total friction of PMSG rotor*
K_M	*flux machine constant*
ω_{win}	*wind speed*
P_w	*wind power*
C	*DC link capacitor*
L_o	*output filter inductor*

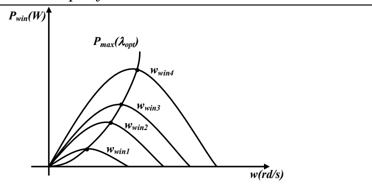

Fig.1. Wind power in function of wind and rotor velocities

2. MODELING THE ASSOCIATION PMSG-AC/DC/AC CONVERTER

The controlled system is illustrated by Fig 2. It includes a 'synchronous generator-AC/DC converter' combination, on one hand, and a single phase DC/AC inverter on the other hand. The circuit operates according to the well known Pulse width Modulation (PWM) principle.

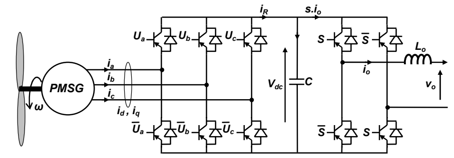

Fig.2. Architecture of AC/DC/AC power converter in wind power systems

2.1 Modeling of the combination 'synchronous generator-PMW DC/AC converter'

Such modeling is generally performed in the *d-q* rotating reference frame because the components i_d and i_q are then the DC currents. According to (Muhammad H, 2001), the model of the synchronous generator, in the *d-q* coordinates, is given by:

$$\frac{d\omega}{dt} = -\frac{F}{J}\omega - \frac{3}{2}\frac{K_M}{J} i_q + \frac{T_g}{J} \quad (1a)$$

$$\frac{di_q}{dt} = -\frac{R}{L} i_q - p\,\omega i_d + \frac{K_M}{L}\omega - \frac{1}{L} v_q \quad (1b)$$

$$\frac{di_d}{dt} = -\frac{R}{L} i_d + p\,\omega i_q - \frac{1}{L} v_d \quad (1c)$$

The turbine power is modelled by $P_w = K_w\,\omega_{win}^3$ where K_w is a constant own to the turbine (see e.g. J. Villanueva, et al, 2008). Also, the input torque is given by $T_g = P_w/\omega$. Then, (1a) can be rewritten as follows:

$$\frac{d\omega}{dt} = -\frac{F}{J}\omega - \frac{3}{2}\frac{K_M}{J} i_q + \frac{P_w}{J\omega} \quad (1d)$$

The converter *d-* and *q-*voltage can be controlled independently. To this end, these voltages are expressed in function of the corresponding control action (see e.g. Michael J, et al, 1998):

$$v_q = v_{dc}\, u_q \quad (2a)$$

$$v_d = v_{dc}\, u_d \quad (2b)$$

$$i_R = 3\left(u_q\, i_q + u_d\, i_d\right)/2 \quad (2c)$$

where $(u_q,\ u_d)$ are the Park transformation of $(u_a,\ u_b,\ u_c)$

with: $u_i = \begin{cases} 1/2 & \text{if } U_i \text{ is } ON \text{ and } \overline{U}_i \text{ is } OFF \\ -1/2 & \text{if } U_i \text{ is } OFF \text{ and } \overline{U}_i \text{ is } ON \end{cases} \quad i = a,b,c$

The considered converter control design will be based upon the following average version of (3a-c):

$$v_q = v_{dc}\, u_1 \quad (3a)$$

$$v_d = v_{dc}\, u_2 \quad (3b)$$

$$\bar{i}_R = 3\left(u_1\, i_q + u_2\, i_d\right)/2 \quad (3c)$$

where $u_1 = \overline{u}_q,\ u_2 = \overline{u}_d$ are the average modulation indexes in the *q-* and *d-*axis, respectively. Similarly, let us introduce the state variables $x_1 = \omega^2$, $x_2 = i_q$, $x_3 = i_d$. Then, substituting (3a-b) in (1b-d) yields the following state space representation of the combination 'PMSG-converter':

$$\frac{dx_1}{dt} = -2\frac{F}{J}x_1 - 3\frac{K_M}{J}x_2\sqrt{x_1} + 2\frac{P_w}{J} \quad (4a)$$

$$\frac{dx_2}{dt} = -\frac{R}{L}x_2 - p\sqrt{x_1}\,x_3 + \frac{K_M}{L}\sqrt{x_1} - \frac{1}{L}u_1 v_{dc} \quad (4b)$$

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