Renewable Energy 63 (2014) 37–45

Contents lists available at ScienceDirect

Renewable Energy

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

Wind turbine controller comparison on an island grid in terms of frequency control and mechanical stress

Haritza Camblong [a, b, *], Ionel Vechiu [b], Xavier Guillaud [c], Aitor Etxeberria [a, b], Stéphane Kreckelbergh [b]

[a] *Department of Systems Engineering and Control, University of the Basque Country (UPV/EHU), Polytechnical University College, Europa Plaza 1, 20018 Donostia-San Sebastián, Spain*

[b] *ESTIA Research, Technopole Izarbel, 64210 Bidart, France*

[c] *L2EP, Cité Scientifique BP 48, 59651 Villeneuve d'Ascq Cedex, France*

ARTICLE INFO

Article history:
Received 26 March 2013
Accepted 28 August 2013
Available online 24 September 2013

Keywords:
Wind turbines
LQG controller
Mechanical stress reduction
Primary frequency control
Island power system

ABSTRACT

The aim of this paper is to present a linear quadratic Gaussian (LQG) controller designed with two main objectives: to allow the contribution of wind turbines (WTs) to the primary frequency regulation of an island power system, and to reduce the WTs drive-train mechanical stresses. The designed LQG1_CPC_Track controller is compared, in terms of the mentioned objectives, to a more classical controller containing two uncoupled control loops. The comparison is carried out in a simulation model of the Guadeloupian island power system taken as a case study. The model is implemented in Eurostag software. Simulation results show that the contribution of both controllers to the primary frequency regulation is satisfactory, and that the LQG1_CPC_Track allows reducing drive-train mechanical stresses significantly. Thus, thanks to the LQG1_Track, on top of allowing the integration of more wind energy in the grid with the contribution to primary frequency regulation, WTs would have less maintenance costs and could be manufactured with cheaper material.

1. Introduction

As the penetration of wind power continuously increases, the impacts of wind power on power system frequency control have become of great concern [1]. Results depicted in Ref. [1] show that control performance standards indices in interconnected system deteriorate as wind power penetration increases. Authors add that this situation could be improved by, among others, increasing forecast accuracy to track fast wind power variations, increasing primary frequency control capability and exerting wind power variation controls.

This problem related to the penetration of wind power in the grid is still more significant in island power systems [2], to the extent that island grids are weaker. Thus, more and more grid codes require that wind turbines (WTs) contribute to the primary frequency regulation [3].

Other very topical issues concerning WTs control are related to mechanical stress reduction [4]. Indeed, most costly mechanical components' stresses or fatigue loads have to be alleviated in order to allow the use of less and/or new materials (eg. fiberglass composites) when manufacturing these components, to reduce maintenance time and to make them more reliable. Achieving these objectives leads to a reduction of the wind energy production cost.

Among the scientific literature, it is very difficult to find works where WTs are controlled at the same time to reduce fatigue loads and to contribute to the primary frequency regulation. However, many papers can be found about the design of controllers for each objective separately.

Concerning the contribution of WTs to the primary frequency regulation [5], and [6] were among the first to propose a modulation of the electrical power produced by WTs in relation to the grid frequency. Reference [7] shows that as variable-speed WTs displace conventional synchronous generation, the frequency nadir following a loss of generation reduces. To face this problem, an inertial response similar to a conventional synchronous generator should be added. Thus, in Refs. [8] and [9], an additional torque depending on the frequency and its rate (as in Ref. [7]) is added to the generator torque reference. In Ref. [10], instead of a torque, it is a power which is added to the power reference. The characteristics of

* Corresponding author. Department of Systems Engineering and Control, University of the Basque Country, (UPV/EHU), Polytechnical University College, Europa Plaza 1, 20018 Donostia-San Sebastián, Spain. Tel.: +34 943018681.

E-mail addresses: h.camblong@estia.fr, aritza.camblong@ehu.es (H. Camblong), i.vechiu@estia.fr (I. Vechiu), xavier.guillaud@ec-lille.fr (X. Guillaud), a.etxeberria@estia.fr (A. Etxeberria), s.kreckelbergh@estia.fr (S. Kreckelbergh).

0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.08.045

Nomenclature

α_p	proportion <1 of the available WT power
β	blades pitch angle
β_{ref}	blades pitch angle reference
$\gamma_{\Omega T}$, γ_v, γ_β	T_a partial derivatives with respect to Ω_T, v and β around the OP
λ	tip speed ratio
σ_v	standard deviation of wind speed
θ_T, θ_G	angular positions of the rotor and the generator
Ω_T, Ω_G	rotational speeds of the turbine and the generator
$\Omega_{G,nom}$	generator rotational speed nominal value
$\Omega_{T,,ref}$	WT rotational speed reference
τ_v	wind speed time constant
τ_β	pitch actuator time constant
n_{eq}	number of cycles of fatigue loads
q_w, q_p, q_D, r_e, r_β	optimizing criteria weights
$\boldsymbol{r}$	reference vector
u	input vector
v	wind speed seen by the WT
v_y	output disturbance vector
v_{nom}	nominal wind speed
w	input disturbance vector
x	state vector
$\hat{x}$	estimated state vector
y	vector of measured outputs
z, z_r	output performance vectors
A, B, C, G	state space matrices
C_p	power and thrust coefficients
D_D	drive-train damping coefficients
D	the total fatigue damage
J_T, J_G	turbine and generator moment of inertia
H_T	tower height
K_D	drive-train stiffness coefficients
$\boldsymbol{K_r}$	feedforward gain
$\boldsymbol{K_x}$	state feedback gain
$\boldsymbol{K_e}$	error integration gain
Kv	gain of the spatial filter.
R_{eq}	one equivalent load
R_i	load ranges
R	blades length
P_G	WT generator power
P_{Gnom}	WT rated power
$P_{G,ref}$	WT generator power reference
P_{disp}	available WT power
T_a	aerodynamic torque
T_D	drive-train mechanical torque
T_G	generator torque
$T_{G,max}$	generator torque maximum limit
$T_{G,ref}$	generator torque reference
DFIG	doubly fed induction generator
FL	full load
KF	Kalman filter
LQG	linear quadratic Gaussian
MIMO	multiple input multiple output
MPPT	maximum power point tracking
OP	operating point
POR	primary operating reserve
WF	wind farm
WT	wind turbine

doubly fed induction generator (DFIG) WTs and conventional power plans are compared and the contributions of DFIG to system inertial response and frequency regulation are investigated. Results show that wind farms can participate in system frequency regulation to a certain extent, as a complement to conventional generation.

Beyond the inertial response, in order to give a primary frequency response, WTs must operate in deloaded mode, fixing a primary operating reserve (POR). Refs. [9] and [11] propose to shift the optimal "Torque versus speed" curve to the right. Since the speed is increased, the inertial kinetic energy storage increases either. Depending on the steady state operating point, the pitch actuator may be used or not. A good coordination between torque and pitch control has to be achieved. Reference [9] proposes to allocate the fast inertial effect to the torque control and the steady state reserve to the pitch angle controller. In Ref. [12], the power reserve is obtained with the help of the generator torque control by following a power reference value lower than the maximum power which can be extracted from the wind. The rotational speed reference is the same as in the classic working. Experimental tests carried out on a 2.2 kW test bench validate the proposed strategy. Ref. [13] shows how an optimal primary reserve can be provided by doubly-fed induction generators. The loss of injected power is minimized and the stored kinetic energy maximized. The results show that the ensuing operating points for a constant power reserve follow a curve parallel to that of the maximum power point tracking (MPPT). In Ref. [14] different wind turbine control methods that enable frequency support and control are presented and compared giving the advantages and disadvantages of each method. According to authors, although there appear to be several alternatives for dealing with the effects of wind generation on frequency regulation, more research is needed to determine what approach will be most effective for specific systems.

Regarding the works about fatigue loads reduction, the loads acting on a wind turbine whilst in operation can be divided into aerodynamic and gravity loads (external), and structural loads (internal) [15]. In order to alleviate these loads the control system of a wind turbine should be able to either reduce the fluctuations of the aerodynamic loads or add damping to the structural modes. Most works try do reduce exclusively drive-train fatigue loads as in Refs. [16–18], by dampening drive-train torque fluctuations [17] or simply decreasing generator torque (T_G) activity. In Ref. [19], general mechanical stresses are also reduced by limiting T_G and pitch angle (β) activities. Similarly, in Ref. [20] pitch angle fluctuations are reduced in order to mitigate blades' dynamic loads.

In Ref. [19], a controller designed for primary system frequency regulation and for drive-train loads reduction is presented, but these loads are reduced indirectly, by limiting the pitch angle rate and the rotational speed variations.

The objective of the work presented in this manuscript has been to design a WT controller which contributes to the primary frequency control of a power system (at least as well as a classical PI controller), and which in top of that, damps mechanical stresses of the drive-train. Another research study on this topic has been presented by some authors of this paper in Ref. [21]. There are two main new contributions in this paper:

- The LQG1_CPC_Track (CPC comes from collective pitch control) controller presented in this paper is different from the two LQG controllers of [21]. Their control model and optimizing criteria are distinct, and above all, LQG1_CPC_Track contains an integral action in one loop in addition to a feed-forward loop (see Section 3.2). These components and loops allow tracking effectively a varying power reference, contrary to the LQGs of [21] which have not them.